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ELECTRIC FIELDS IN EARTH ORBITAL SPACE.(U)
MAY 82 W P OLSON, K A PFITZER, S J SCOTTI N00014-80-C-0796
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ELECTRIC FIELDS IN EARTH ORBITAL SPACE

ANNUAL REPORT

CONTRACT N00014-80-C-0796

MAY 1982

MDC-H0087

by

Principal Investigator: W. P. Olson

Co-Investigators: K. A. Pfitzer
S. J. Scotti

Sponsored by
Office of Naval Research
Washington D.C., 20350

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY-HUNTINGTON BEACH
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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: MDC H0087	2. GOVT ACCESSION NO.: AD-A116460
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (*and Subtitle*): ELECTRIC FIELDS IN EARTH ORBITAL SPACE ANNUAL REPORT	5. TYPE OF REPORT & PERIOD COVERED: ANNUAL REPORT
	6. PERFORMING ORG. REPORT NUMBER: MDC H0087
7. AUTHOR(s): W. P. Olson, K. A. Pfitzer, S. J. Scotti	8. CONTRACT OR GRANT NUMBER(s): N00014-80-C-0796
9. PERFORMING ORGANIZATION NAME AND ADDRESS: McDonnell Douglas Astronautics Company, 5301 Bolsa Avenue, Huntington Beach, CA 92647	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: W8QA2001
11. CONTROLLING OFFICE NAME AND ADDRESS: Office of Naval Research, Washington, D.C. 20350	12. REPORT DATE: June 1982
	13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (*if different from Controlling Office*)	15. SECURITY CLASS. (*of this report*): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

induced electric fields, plasma sheet, plasma mantle, boundary layer
magnetosphere
pressure balance
electrostatic fields

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

This is a report of progress during the past year. The work was performed in three areas with a long term goal understanding the formation and maintenance of electrostatic fields in the earth's magnetosphere. The entry of low energy charged particles into a magnetically closed magnetosphere has been examined in some detail. Entry is permitted because of the non-uniform nature of the magnetic field over the magnetopause surface. Electrostatic fields may be formed across the tail of the magnetosphere because of the different "entry efficiencies" of protons and electrons. The consequences of this particle

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SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*) entry mechanism for the plasma sheet, plasma mantle, and boundary plasmas in the magnetosphere are examined. The mathematics of particle entry was investigated in a one-dimensional boundary using both kinetic theory and bulk MHD parameters. From our participation in the 6th Coordinated Data Analysis Workshop, we have determined that at least during disturbed magnetic conditions, currents persist near geoshychronous orbit in the nightime region which are presently not included in our dynamic magnetic field models. These currents are probably associated with the field aligned currents which close in the ionosphere near auroral latitudes.

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1.0 INTRODUCTION

The work of the McDonnell Douglas Group supported by ONR support has always been focused on magnetospheric electric fields. In our early work, we found that in order to quantitativly represent induced electric fields, we had to first accurately model the magnetospheric magnetic field. This took several years and resulted in models that are now used worldwide to represent the extension of the geomagnetic field into space. More recently we have attempted to quantitatively represent the electrostatic fields present in the magnetosphere. The charge separation responsible for this field is inextricably tied to the microphysics of the magnetopause and charged particle entry into a magnetically closed magnetosphere. Thus, again, we found that we must first understand and model another magnetospheric feature--the entry and motion of low energy particles. In particular we have been interested in the formation of the cross tail electric field which is of electrostatic origin.

Our interest in this problem led us to reexamine the classical pressure balance condition which has been used historically to determine the shape of the magnetosphere and the topology of the magnetospheric magnetic field. The pressure balance equation states simply that the transition from the extension of the geomagnetic field to the region of interplanetary space will be found where the energy density (or pressure) of the geomagnetic field is equal to the pressure caused by the streaming solar wind plasma. Implicit in the use of the pressure balance equation is the assumption that the charged particles incident on the magnetic field are reflected specularly; that is, in a mirror like fashion such that a particle's angle of incidence is exactly equal to its angle of reflection. This assumption implies that the magnetic field in the vicinity of the interaction with the incident particle is uniform. We noted as early as our 1974 papers that this was indeed not the case and that gradients in the magnetic field parallel to the magnetopause might be responsible for permitting the entry of a fraction of the incident particles, the size of the fraction being determined by the angle between the incident particle direction and the magnetopause surface.

In the past year and a half, we have explored this more realistic representation of pressure balance with the goal of understanding the entry of the magnetosheath plasma to the magnetosphere. We are now in a position to qualitatively explain the existance of the plasma sheet, boundary layer and plasma mantle regions of the magnetosphere. We are also, of course, interested in understanding better the microphysics of the magnetopause with this new pressure balance formalism. We expect that this work will also lead to a quantitative understanding of the formation of the cross tail electric field. (This relates back to our long term goal of quantitatively representing the total electromagnetic environment for charged particles throughout the earth's magnetosphere.)

This report continues with 3 technical sections. We first discuss qualitatively the entry of plasma into the magnetosphere using a realistic pressure balance formalism. Although most of our results to date on plasma entry are qualitative, we feel that we can explain the presence of most of the magnetosphere's plasma regions in terms of this entry mechanism. In the second section we discuss work performed in the last year on the microphysics of the magnetopause that is tied to our understanding of the entry mechanism discussed in the previous section. Although some interesting work has been performed, our tentative conclusion on the microphysics problem is that it will require more resources to solve and that it must be solved in advance of our work on the representation of the cross tail electrostatic field. The last section provides up to date information on our participation in the Coordinated Data Analysis Workshop activities with emphasis on CDAW-6 which is in progress. These workshops have provided us much valuable quantitative information on the accuracy of our magnetic field models and on the dynamic properties of the magnetosphere generally.

2.0 THE ENTRY OF LOW ENERGY PARTICLES INTO A MAGNETICALLY CLOSED MAGNETOSPHERE

This section is divided into two parts. In the first we discuss quantitative work that has been done in the past year. In it we also discuss problems regarding the data base (in particular limited information on particle distribution functions in the magnetosheath region) and the impact that has on future quantitative work. In the second section qualitative aspects on particle entry into the magnetosphere are discussed generally in terms of our nonspecular reflection model of the pressure balance condition.

2.1 Quantitative Work

We have explained in earlier reports our quantitative procedures for determining charged particle entry through the magnetopause. This is done by computer and involves several codes. First an accurate description of the magnetic field topology at the magnetopause is required for the quantitative representation of gradients in the magnetic field. It is the gradient in the field that causes the particles to not reflect specularly from the magnetic field, allowing some of them to remain in the magnetosphere. This process is shown in Figure 1. Another code calculates the Lorentz force on the charged particle and is used to determine the trajectory of the particle in the magnetospheric magnetic field. At a given point on the magnetopause, particles are allowed to impact with varying angles to the surface normal. Last year we developed a graphic representation for the "entry cone", that is, the solid angle region through which particles may impact the magnetopause and then remain in the magnetosphere due to the non-uniform magnetic field. An example of this representation is shown in Figure 2. Note that the "entry fraction" depends on the position on the magnetopause, the particle type (i.e., proton, electron, helium nucleus), and the the particle energy. The entry fraction is the ratio of the solid angle for entering particles to the total solid angle at the point in question. It also represents that fraction of isotropic magnetosheath plasma particles that would enter the magnetosphere. Since the magnetosheath plasma possesses an anti-solar bulk flow direction, the actual percent of incident plasma particles that enter the

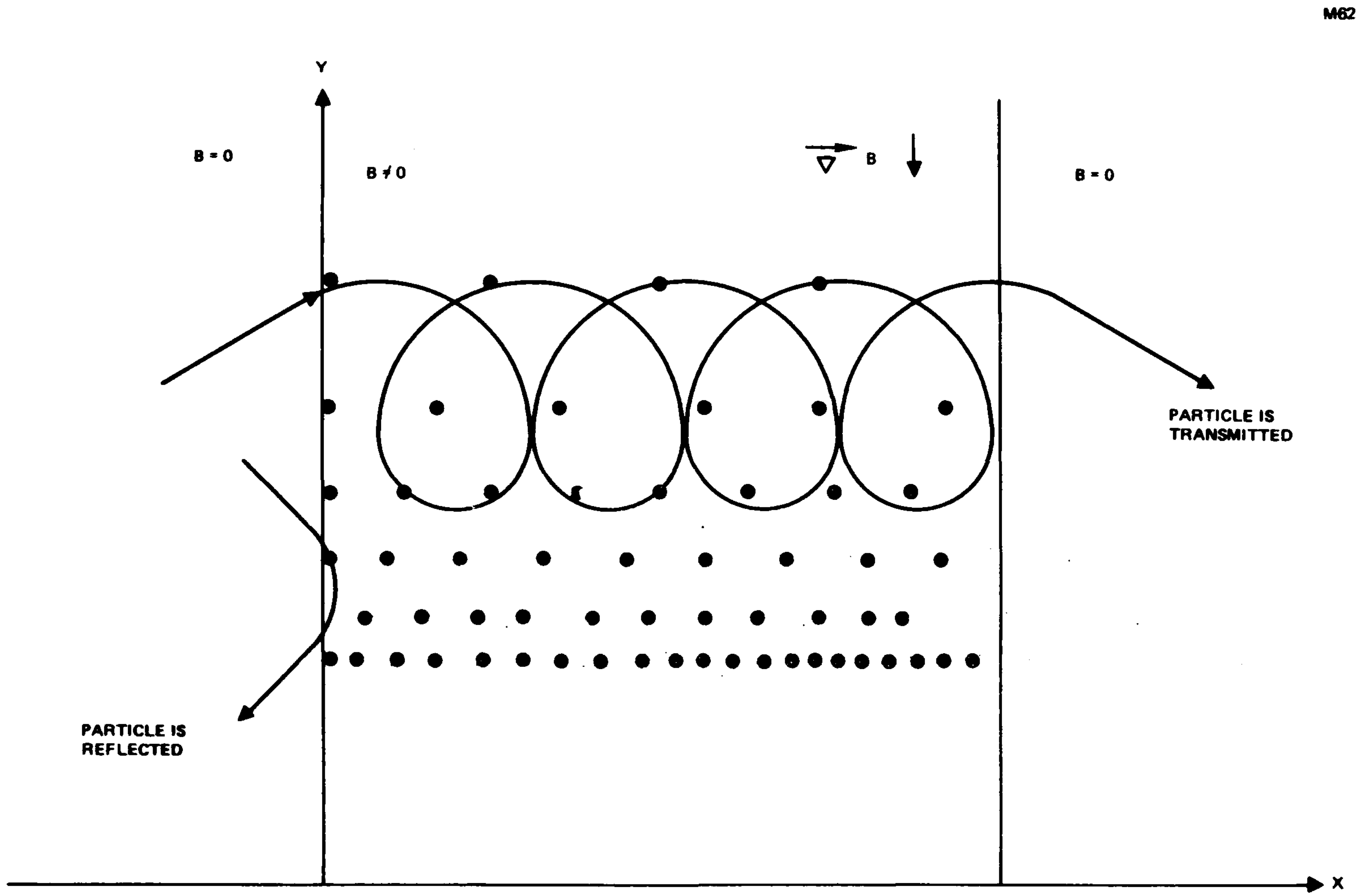
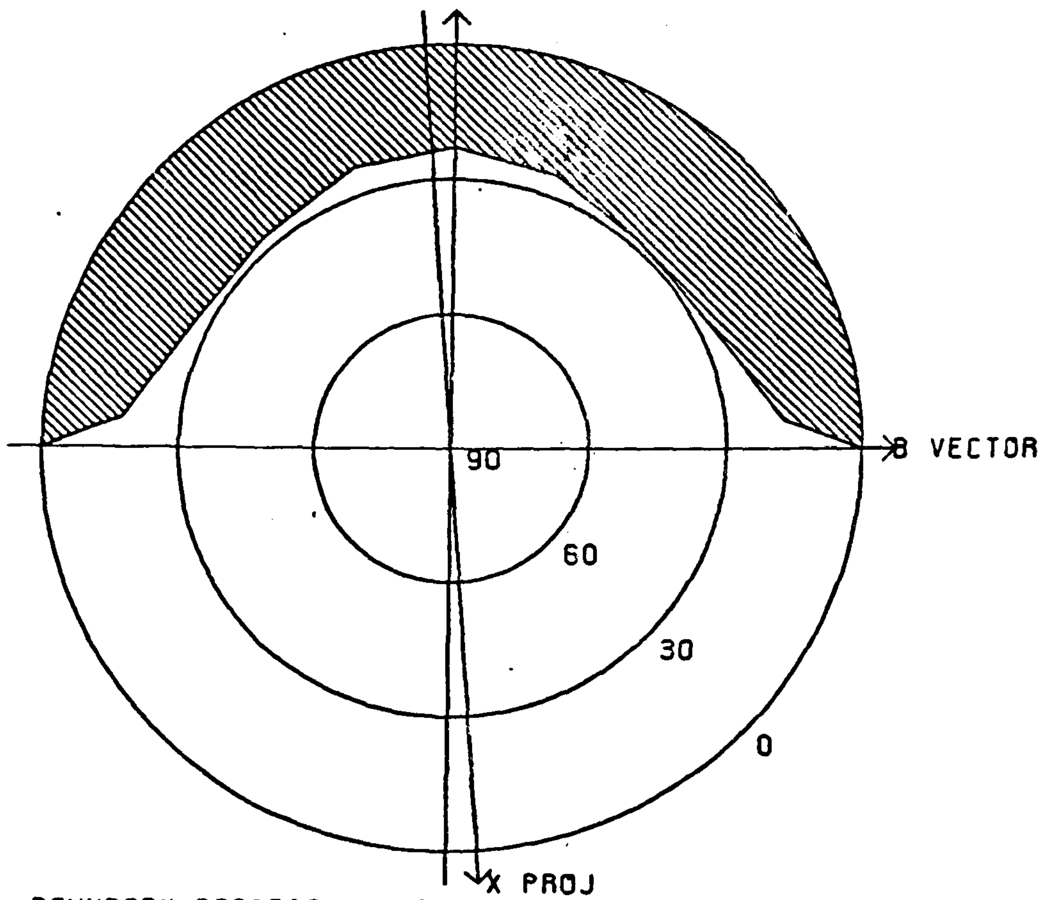


Figure 1.

PROTON ENTRY INTO MAGNETOSPHERE



BOUNDARY POSITION: -20.00 -18.03 0.63

BOUNDARY NORMAL: -0.0186 -0.9997 0.0162

ENERGY (KEV) : 5 ENTRY FRACTION: 0.0946

PARTICLES GOING IN THE DIRECTION OF SHADED PORTIONS ENTER

Figure 2

magnetosphere at any point will be somewhat larger than the entry fraction numbers discussed in this section. For a more realistic representation of the magnetosheath plasma, particle distribution functions must be used.

The representation of the solid angle for entering particles shown in Figure 2 is of limited usefulness because it discusses particle entry only at a point on the magnetopause. This work was extended to many points over the tail of the magnetosphere in order to provide a picture of particle entry as a function of location on the magnetopause and in terms of particle energy. This discription is provided in Figures 3 through 5 which show particle entry into the tail of the magnetosphere for one, five and ten kilovolt protons at different distances down the tail. It is noted that the entry fraction is quite sizable near the equator but quickly diminishes at off equatorial locations. This is clearly consistent with observations of the plasma sheet which persists across the equatorial region of the tail with a maximum thickness of about 8 earth radii near the flanks (i.e., the region in the equatorial tail near the magnetopause boundary). Note that for 10 kilovolt protons the entry fraction is almost .3, that is, approximately 30% of the incident protons at a distance of 40 earth radii down the tail enter the magnetosphere. We note also that because of the magnetic field topology, particles more than 20 degrees above the equator in the tail region, even if they do enter, flow along magnetic field lines in the anti-solar direction. Thus the only portions of the tail that are traversed by charged particles originating in the magnetosheath region are in the plasma sheet and in a narrow boundary layer that surrounds the northern and southern extremities of the cross section of the tail. The regions in between (the lobes) are characterized by the persistence of a magnetic field and a very low plasma density. This is because the lobe regions are not connected to the magnetosheath particle source by magnetic field topology. More is said on this subject in the section on qualitative results.

As a corollary exercise, we have quantitatively examined the implications of this particle entry on the pressure balance equation, the magnetopause shape, and the change in the strength of the magnetic field at the location of the

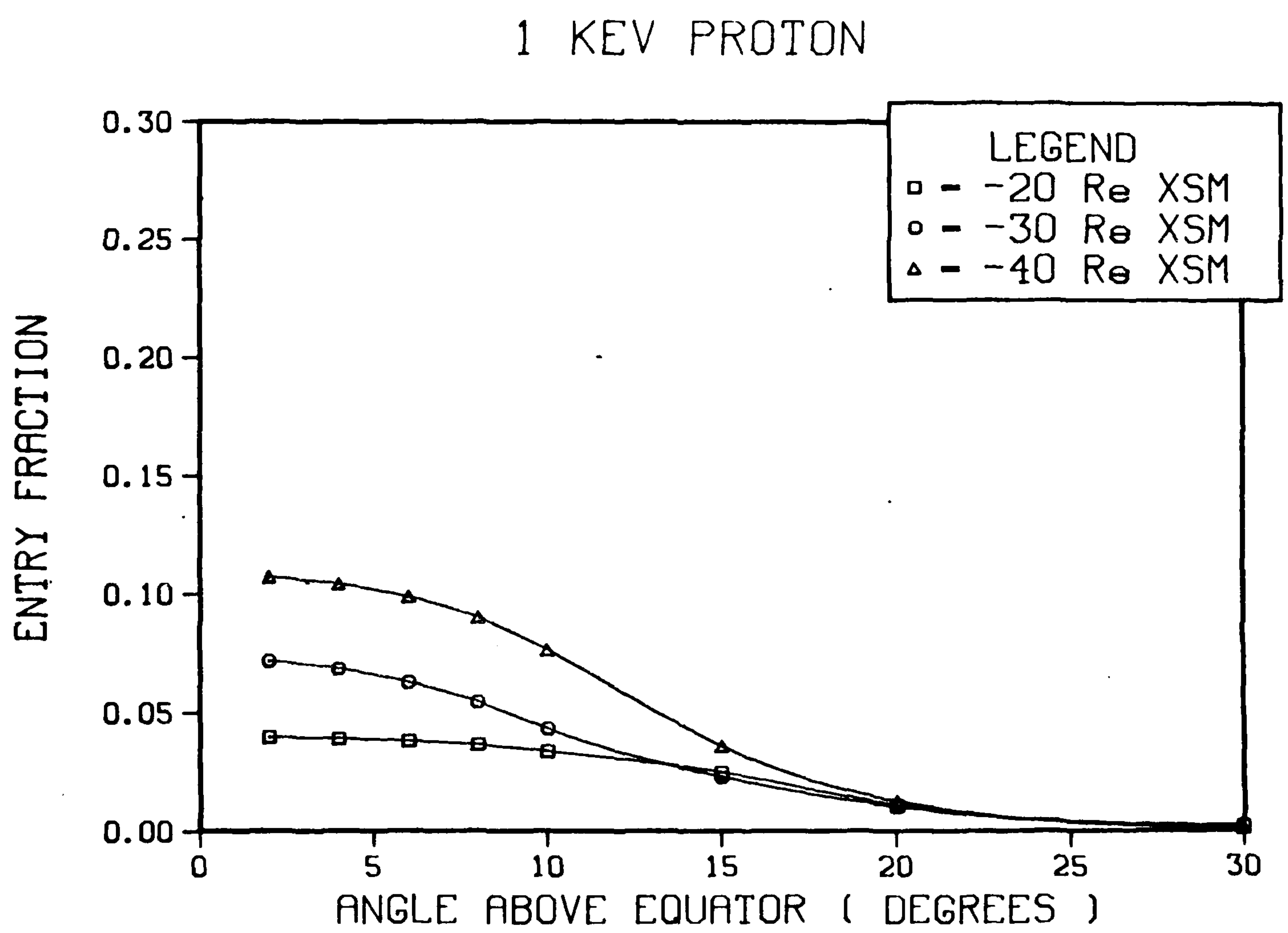

1 KEV PROTON
LEGEND
-20 Re XSM
-30 Re XSM
-40 Re XSM
ENTRY FRACTION
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
5
10
15
20
25
30
ANGLE ABOVE EQUATOR (DEGREES)

Figure 3

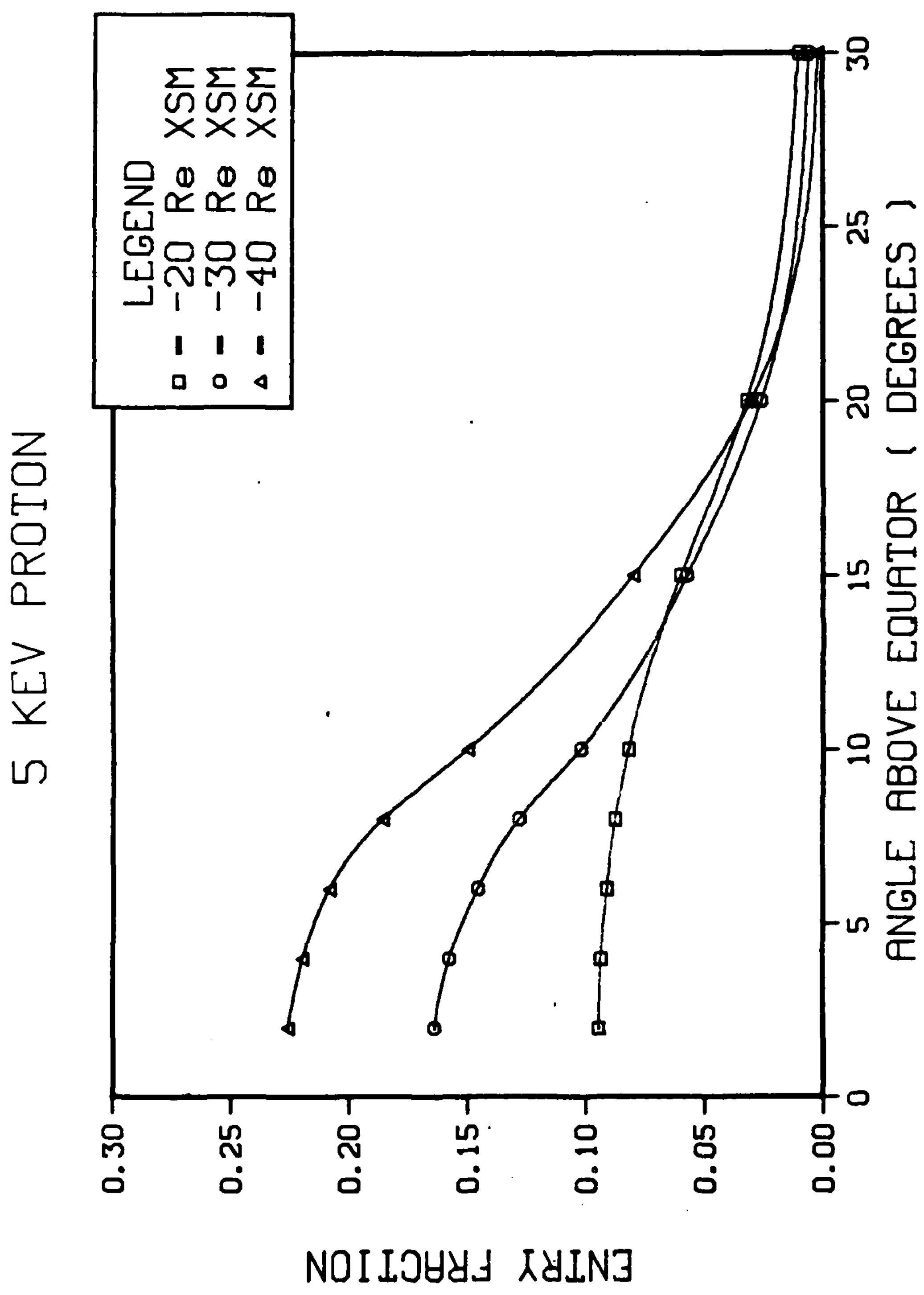
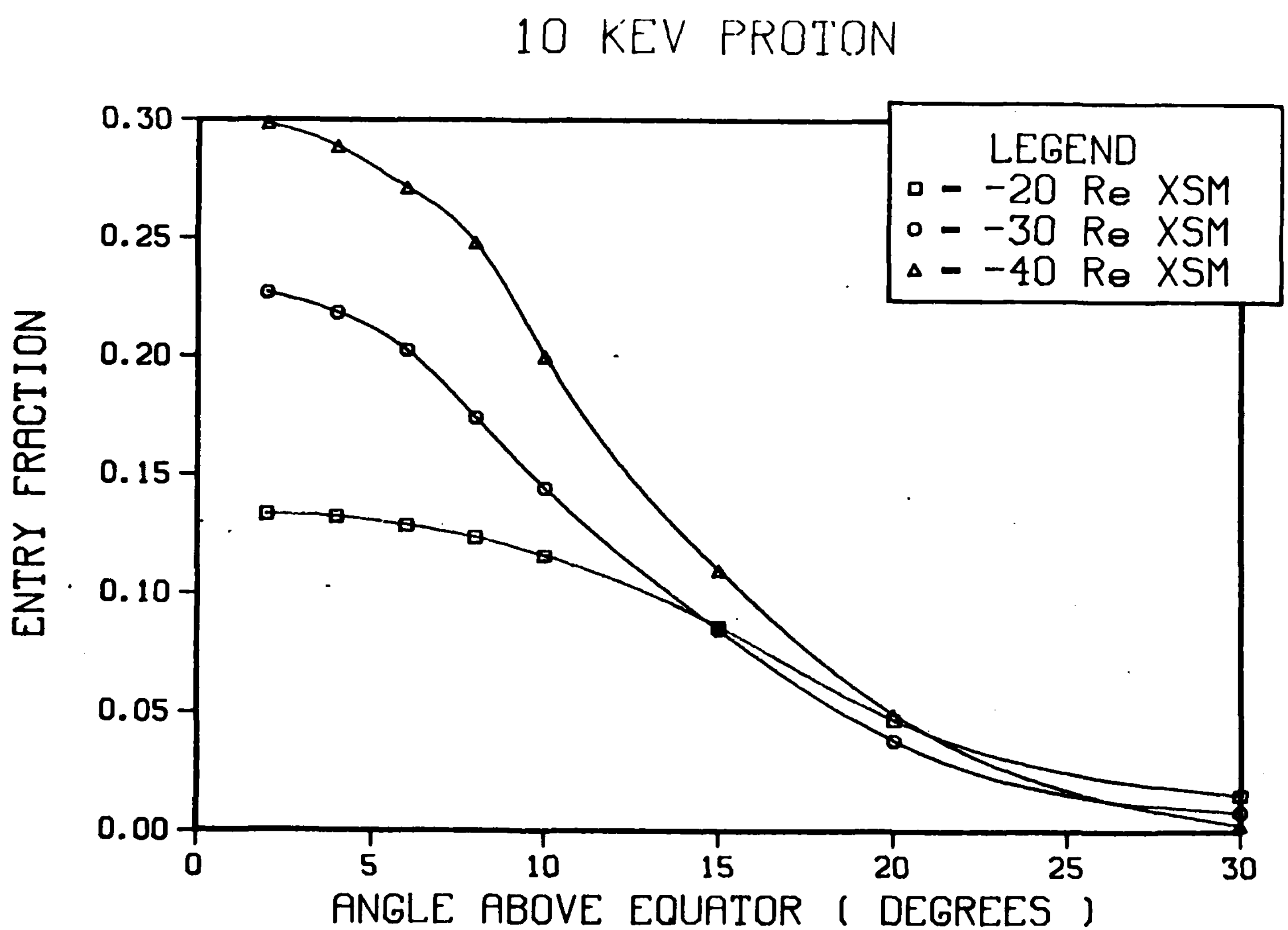

5 KEV PROTON
LEGEND
-20 Re XSM
-30 Re XSM
-40 Re XSM
ENTRY FRACTION
0.00
0.05
0.10
0.15
0.20
0.25
0.30
ANGLE ABOVE EQUATOR (DEGREES)
0
5
10
15
20
25
30

Figure 4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LEGEND
- -20 Re XSM
- -30 Re XSM
- -40 Re XSM
ENTRY FRACTION
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
5
10
15
20
25
30
ANGLE ABOVE EQUATOR (DEGREES)

Figure 5

magnetopause. When 25% of the plasma incident on the region of the magnetopause enters the magnetosphere, the pressure at the magnetopause is over estimated by 12-1/2%. (The pressure balance condition assumes a factor of 2 for the incident charged particles since they are reflected. Entering particles will still create pressure in the boundary but only half as much as the reflected particles). This change in pressure will act to increase the geocentric distance to the magnetopause by about 3% and act to decrease the magnetic field there by approximately 6%. Thus the changes in magnetopause shape and magnetic topology are noticable but minor and in the proper direction. That is, they make the tail slightly more tail-like (a non dipolar field geometry) than shown in existing magnetic field models. We therefore conclude that this entry mechanism produces only minor changes and that it continues to be appropriate to use the old pressure balance formalism to determine magnetopause shape and field topology.

Again, however, we wish to emphasize that by relaxing the specular reflection condition in the pressure balance equation, we are able to explain the entry of low energy particles into a magnetically closed magnetosphere. Low energy particle entry through the magnetopause occurs virtually at all locations. Magnetic field topology within the magnetosphere determines the subsequent motion of the particles. It is only in the equatorial region of the tail (the plasma sheet region) that magnetosheath plasma has direct access to regions deep in the magnetosphere. More is said concerning the supply of magnetosheath plasma to the magnetosphere in the following section.

2.2 The Supply of Magnetosheath Plasma to the Magnetosphere

Although much work to date has been done on the quantitative aspects of low energy charged particle entry, problems remain with the quantitative calculation of magnetospheric plasma densities based on magnetosheath plasma values because of the small amount of data on magnetosheath plasma properties. We feel however, that it is important to discuss qualitatively those features of magnetospheric plasmas that can be explained in terms of low energy particle entry through the magnetopause. We believe these include the existence of all quiet time plasma features found in the mid magnetosphere and the tail. Near synchronous orbit the ring current and the plasmasphere are populated by particles originating in the ionosphere and by particles that have been accelerated inward from the tail region during dynamic magnetospheric events. Their existence thus cannot be explained directly in terms of a magnetosheath source plasma.

Thus, in order to determine which regions of the magnetosphere are populated by particles from the magnetosheath it is necessary to understand the magnetic control of particle motions within the magnetosphere.

To discuss particle motions in the magnetosphere, it is appropriate to begin with the equatorial region. Particles with 90 degree pitch angles (their velocity vector perpendicular to the direction of the magnetic field) will remain in the equatorial plane. Furthermore, particles in a static magnetic field configuration will move along lines of constant total magnetic field. Contours of constant magnetic field are shown in Figure 6. It is seen that there is a region in the inner magnetosphere where the contours do not intersect the magnetopause. It is this region and the lobes of the tail that are not directly linked to the magnetopause and therefore cannot directly receive plasma from the magnetosheath region. Throughout the remainder of the equatorial magnetosphere, some of the particles impacting the magnetopause will gain access to the magnetosphere and drift across and out the other side. As shown in Figures 3 through 5, the number of incident particles entering the magnetosphere increases with distance down the tail. Also, since the magnetic field is uniform at the subsolar point (the intersection of the sun-earth line with the magnetopause) it is expected that the entry fraction near the nose of the magnetosphere will be quite small. Thus, in the equatorial region, there exists an inner magnetosphere area where no magnetosheath particles have direct access. Moving along the magnetopause tailward, the number of entering particles increases gradually so that at about $x_{sm} = -8\ R_e$ the inner edge of the plasma sheet is encountered. Note that for 90 degree pitch angle particles the inner edge of the plasma sheet can be no closer than about 7 R_e from the center of the earth during undisturbed magnetic conditions.

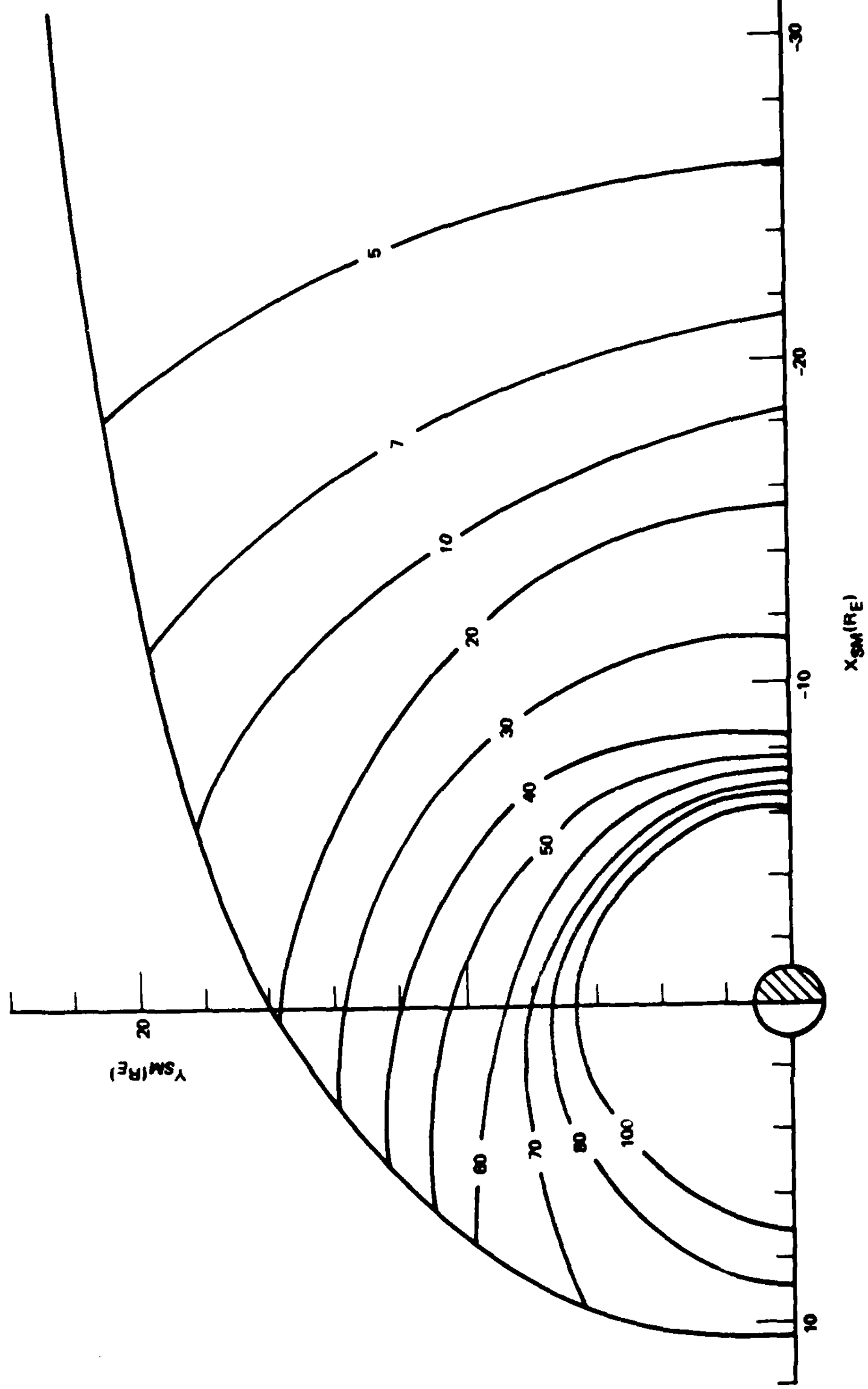
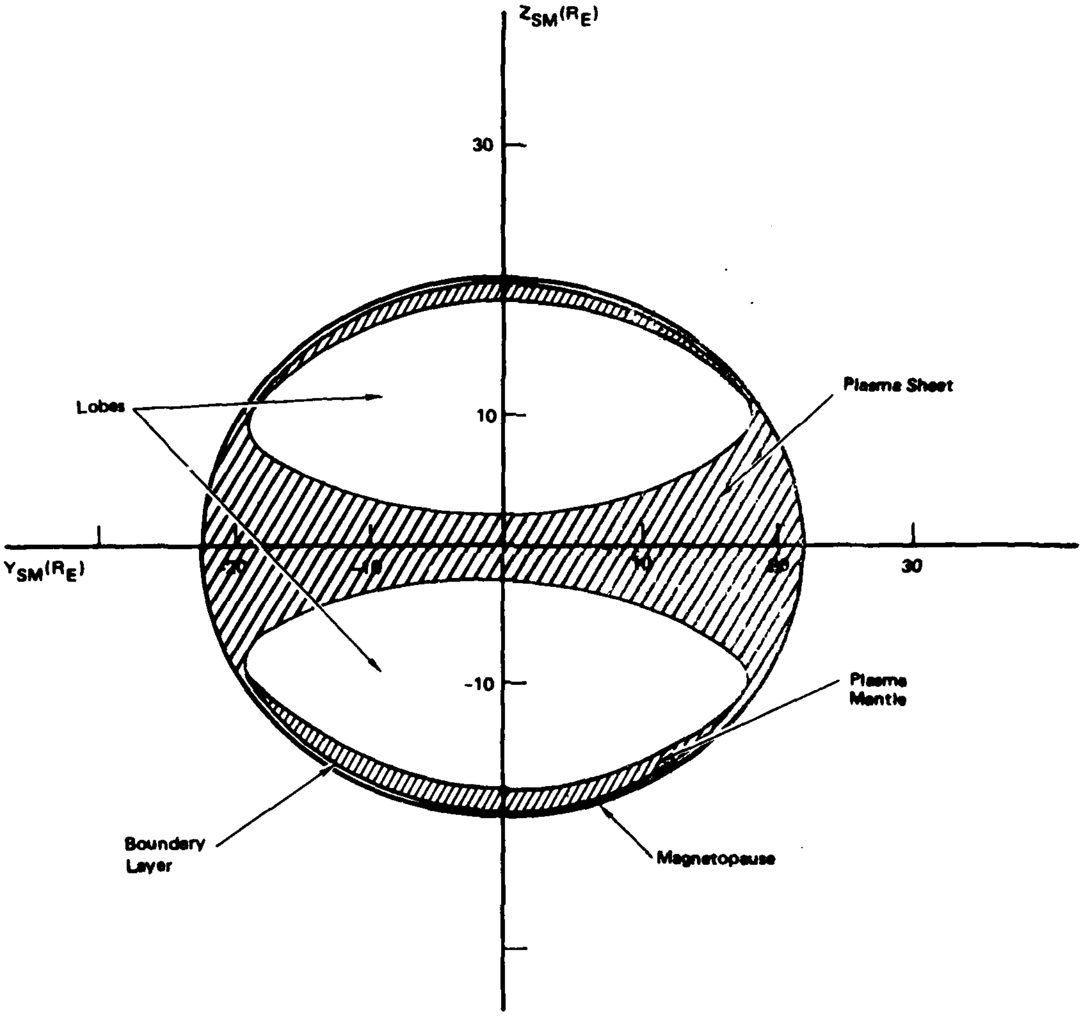


Figure 6

When the discussion of particle entry is expanded to include non-equatorial particles (i.e., those with pitch angles other than 90 degrees) things become more complicated since, in addition to the gradient drift, the particles also move up and down along field lines. However, it is the non-equatorial particles in the magnetosphere that populate the plasma sheet, the plasma mantle, and boundary layer plasmas. We believe that the existence of these different plasma populations in the magnetosphere can be attributed to one phenomenon; the entry of low energy plasma into a magnetically closed magnetosphere. Also note that although the following discussion is qualitative with regard to charged particle densities, the comments on the locations of these various plasmas within the magnetosphere are quantitative. A cross section of the magnetospheric tail is shown schematically in Figure 7 where several observed features are noted. The plasma sheet persists through the center of the tail, narrower in the center (about 2 earth radii thick) and expanding to 6 to 8 earth radii near the flanks of the magnetosphere. The change in thickness of the plasma sheet can be explained in terms of charged particle entry and magnetic field topology. As seen in Figures 3 through 5, substantial amounts of plasma enter the magnetosphere only within about 20 degrees of the equator. Quantitative models of the magnetospheric magnetic field show that field lines close to the flanks of the tail are more dipolar in shape than those near the center of the tail. Thus as charged particles in the plasma sheet cross the tail, they move through a narrow region in the center of the tail (see Figure 7).

Two more magnetospheric plasmas are shown in Figure 7. First of all there is a boundary layer plasma shown just inside of the magnetopause above and below the lobe regions. This boundary layer is thought of as an extenstion of the magnetopause. Technically, however, the magnetopause describes that region where the magnetic field abruptly changes magnitude. The boundary layer plasma can be explained in terms of our entry mechanism as consisting of charged particles that have not been reflected by the geomagnetic field but rather have gained entrance to that region of the magnetosphere. The internal magnetic field topology, however, prohibits these particles from moving

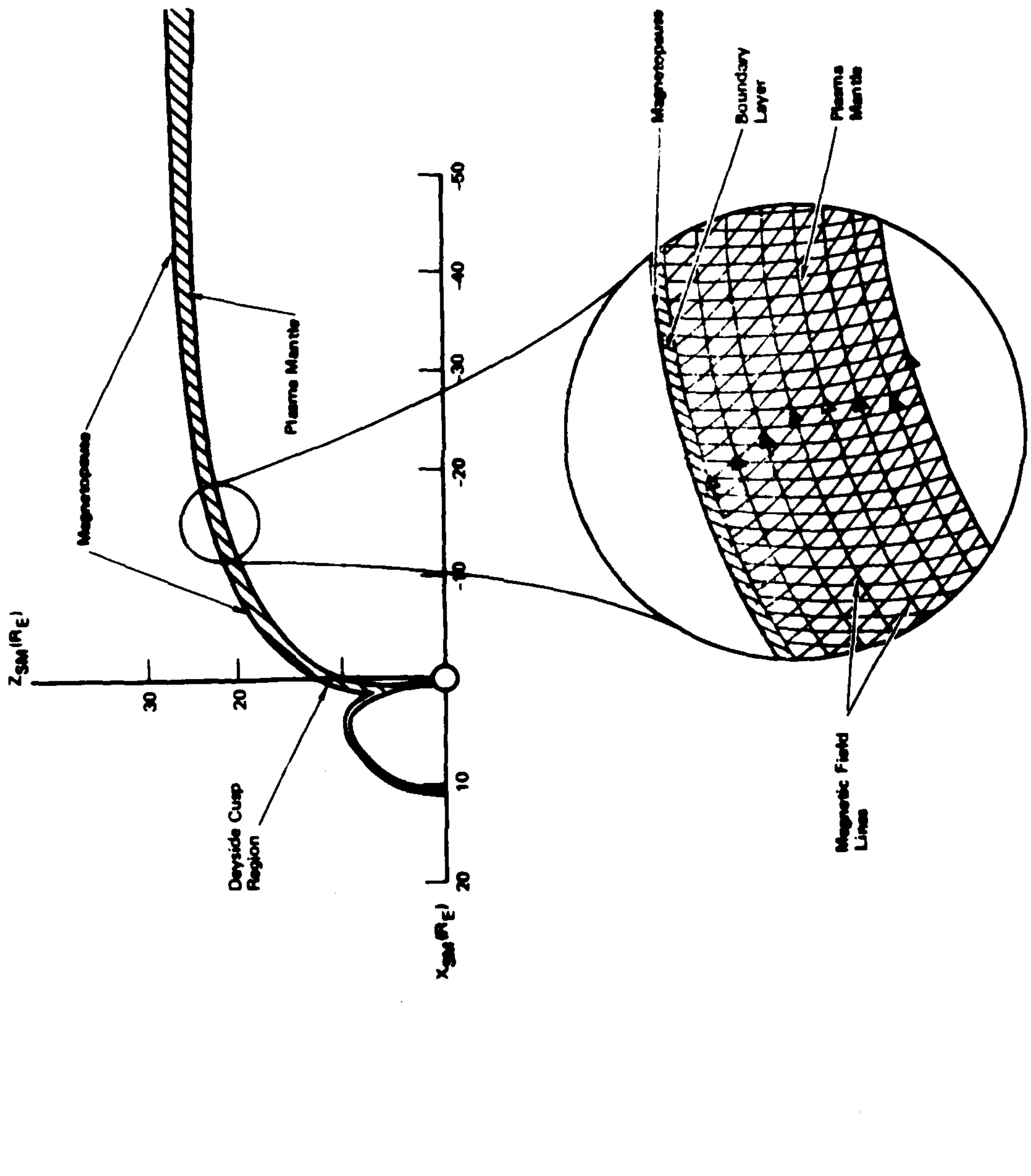


$Z_{SM}(R_E)$
30
10
-10
$Y_{SM}(R_E)$
30
Lobes
Plasma Sheet
Plasma Mantle
Boundary Layer
Magnetopause

Figure 7

further into the magnetosphere, instead, they move along magnetic field lines down the tail and remain confined to a region of space close to the magnetopause. The third region of plasma shown in Figure 7 is the plasma mantle. It persists just inside of the boundary plasma and at mid tail distances has a thickness of about 1 earth radius. In between the mantle plasma and the plasma sheet, are two regions referred to as the lobes of the tail that are described primarily in terms of the magnetic field which persists there. The lobe regions are almost devoid of plasma because they are not connected magnetically to the magnetopause. That is, there is no way for magnetosheath particles, even once they have gained access to the magnetosphere, to move into the lobe regions. In the terminology of cosmic ray physics, the lobes are magnetically forbidden regions. Another magnetically forbidden region occurs in the inner magnetosphere (see Figure 6 and the discussion above).

In order to further explain the existence of the boundary layer and the plasma mantle, it is necessary to discuss the neutral point and cusp regions of the magnetosphere. In early magnetospheric magnetic field models, it was found that there are two neutral points where the total magnetic field vanishes. All magnetic field lines on the magnetopause emanate from these two neutral points. Later it was observed that the real magnetosphere does not possess neutral points, but in their place the "day side cusps". This cusped geometry is shown in Figure 8 in a noon-midnight meridional cross section. Along the magnetopause, it is seen that entering particles are free to move over a confined region that constitutes the boundary layer. It is noted that particles which enter the magnetosphere deep in the cusp region form an expanded plasma layer as they propagate back to the tail. This is the plasma mantle. The reason that the plasma mantle expands to about one earth radius is explained simply in terms of the change in the strength of the magnetic field. In order for the charged particles to maintain their magnetic moments, their gyroradii must increase inversely proportional to the strength of the magnetic field. Since they move from a magnetic field, which has a strength of 50 to 75 gammas to a region in the tail where the field has weakened to only a few gamma, the gryo radii of the particles increase from about 100 kilometers to a substantial fraction of an earth radius.



Magnetopause
Plasma Mantle
Magnetopause
Boundary Layer
Plasma Mantle
Dayside Cusp Region
Magnetic Field Lines
Z_SM (R_E)
X_SM (R_E)
30
20
20
10
-10
-20
-30
-40
-50

Figure 8

It is noted that all of the work reported here has been done for static magnetospheric conditions. We realize that many interesting magnetospheric phenomena require an understanding of the magnetosphere's dynamic response to changes in solar wind and interplanetary parameters. In fact our long term goal, stated elsewhere in this report, is to understand and quantitatively describe the time varying electric and magnetic fields which reside in the magnetosphere so that they may be used to study dynamic plasma behavior in the earth's magnetospheric "laboratory". This work on plasma entry should help us toward that goal. It is interesting to note that particles which constitute the boundary layer and plasma mantle stay in the magnetosphere only several minutes since they flow along magnetic field lines. This is in striking contrast with the particles that move across the plasma sheet. Typically it will take a one kilovolt proton with a small pitch angle approximately 3 days to move across the tail. This difference in "magnetospheric residence" times has important implications for magnetosphere dynamics since magnetospheric substorms occur typically every few hours. Thus a particle moving across the plasma sheet will probably be energized and deenergized over a dozen times during its journey through the magnetosphere or it may be injected into the ring current region and finally precipitate into the atmosphere.

3.0 MAGNETOPAUSE MICROPHYSICS

In a sense the work described in the preceding section has been an "aside". It is peripheral to our primary goal and yet, like our earlier excursion into magnetic fields, we feel that the work on charged particle entry into a magnetically closed magnetosphere is an important subject in magnetospheric physics in its own right. However, we have continued work on magnetopause microphysics in an attempt to reach our goal of quanitiatively understanding the formation of charge separation in the tail region that supports the cross tail electric field. We have found this to be an exceedingly complex problem and, in fact, one unlike any others we have worked on to date. This is because it is both local and global as explained below. We have shown above that a fraction of the incident protons enter the magnetopause, a portion of them moving across the tail to form the plasma sheet. However, the protons enter only on the dawn side of the magnetosphere. None enters on the dusk side because of the field topology. The opposite is true of electrons; they enter on the dusk magnetopause, but not on the dawn side. If all things were equal, eventually the electrons and protons would drift across the magnetosphere forming both the plasma sheet and the cross tail current system that supports the lobe magnetic field. However, there remains an exciting problem since the entry fractions for the protons and electrons are not the same. Thus, even for a charge neutral isotropic plasma existing in the magnetosheath region, more protons will enter on the dawn side than electrons on the dusk side. We conclude therefore that the work described in the preceding section is approximate and that in order to properly understand (1) charged particle entry into the magnetosphere, (2) the microphysics of the magnetopause, and (3) the formation of the cross tail electric field, it is necessary to develop a self consistent description of the magnetopause magnetic field and the magnetic field interaction with the magnetosheath plasma. The solution to this complicated problem would provide quantitative information in each of these areas. The solution, however, is difficult because in addition to requiring the self consistent description of the interaction between the plasma and the field at a point on the magnetopause, it must take into account the effects of the electric field caused by charge separation across the magnetosphere due to differences in the entry efficiencies of electrons and protons.

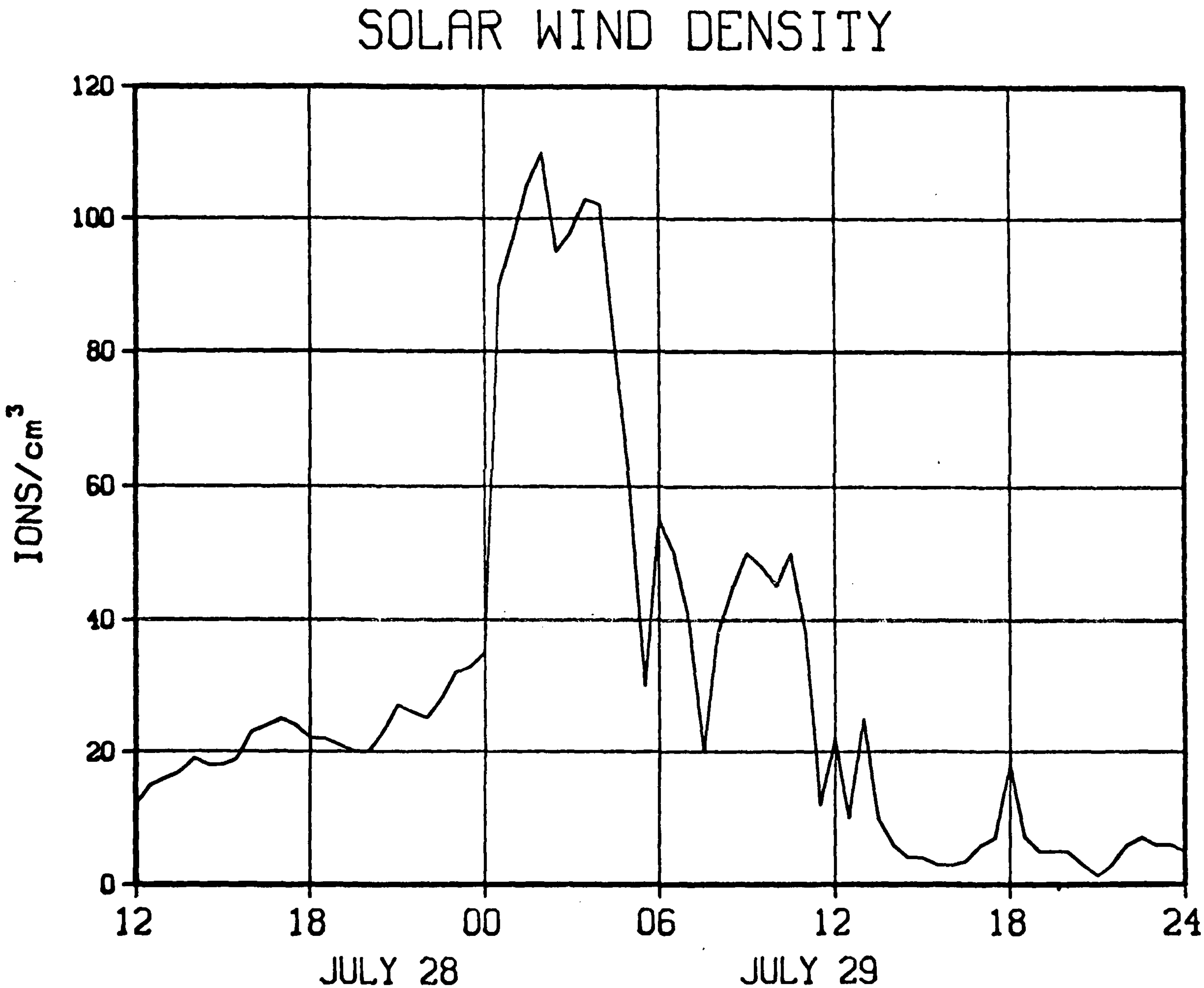
In an attempt to understand the entry problem on a more physical basis, two one-dimensional models of the magnetopause were developed. A description of the mathematical aspects of the models is given in Appendix A. Note that the narrative and equations in the Appendix were done on one of our word processors that we are just now learning how to use. It provides text book quality copy (the work really was done by our group).

In the first one-dimensional problem, an MHD macrophysical model was developed which led to the classical pressure balance equation. This model was used to show that any electrical field present in the magnetosphere must be very large before it will impact pressure balance (on the order of 1 volt per meter). Electric fields observed in the magnetosphere tend to be in the millivolt per meter range so it is appropriate in the pressure balance formalism to neglect the pressure caused by magnetospheric electric fields. In the second one-dimensional problem, kinetic theory was used. Of the possible solutions that could be examined only one was carried through in closed form. It allows the presence of the electric field in the mangetosphere but does not permit particle entry. This work points out the difficulty of determining with mathematical rigor the microphysics of magnetopause structure. Clearly more work must be performed on this problem.

4.0 PARTICIPATION IN THE COORDINATED DATA ANALYSIS WORKSHOPS

Concurrent with our work on magnetospheric electric fields, we have participated actively in the Coordinated Data Analysis Workshops (CDAW) 1, 2, and 6, which have focused on the dynamic behavior of the magnetosphere by examining specific events. The following paragraphs contain exerpts of work on CDAW described in our December 81 proposal to your office. Since the proposal was submitted, the first of the CDAW 6 meetings was held at Goddard. We also describe our participation in that meeting as it relates to our studies on particle entry and magnetospheric electric fields.

While we were working on the entry problem, CDAW-1 and CDAW-2 were held, both concerned with the description and understanding of the July 29, 1977 event while at CDAW-2 we developed the first quantitative model of a particular event. The magnetopause current strengths and location were determined directly from the solar wind pressure. Figures 9 and 10 show the solar wind density and velocity during the July 29 event. The pressure balance formalism developed almost 20 years ago can be used directly to calculate the size of the magnetosphere. Figure 11 shows the standoff distance for the event. Note that early in the event the magnetosphere is compressed inside of geosynchronous orbit and that later the magnetopause relaxes out to 14 earth radii. The variation in the strength of the magnetopause currents through the event is shown in Figure 12. Thus the field in the noon quadrant is accurately modeled. However, in the antisolar region where the tail currents


SOLAR WIND DENSITY
IONS/cm3
120
100
80
60
40
20
0
12
18
00
06
12
18
24
JULY 28
JULY 29
Figure 9

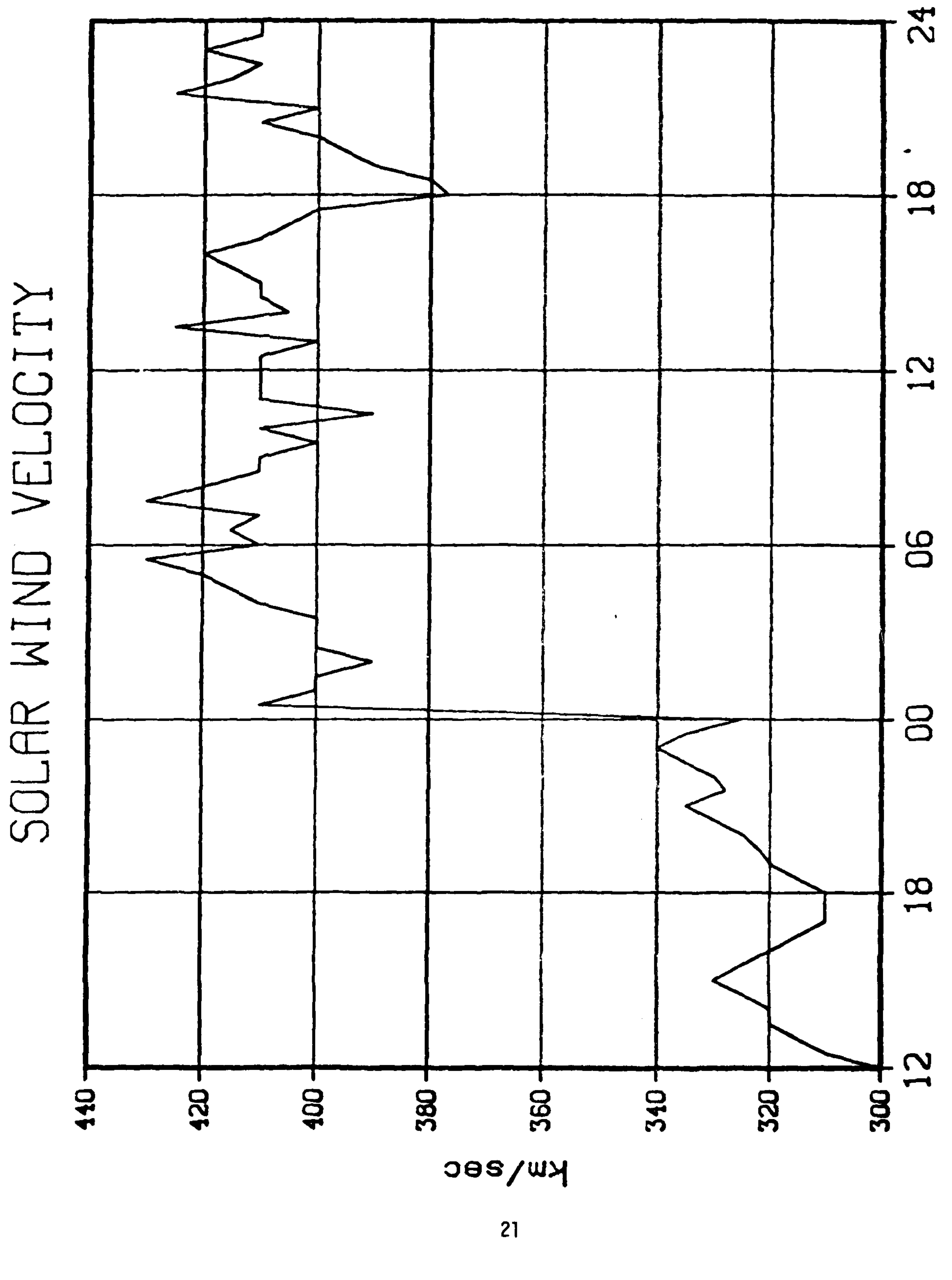

SOLAR WIND VELOCITY
km/sec
440
420
400
380
360
340
320
300
12
18
00
06
12
18
24
JULY 28
JULY 29

Figure 10

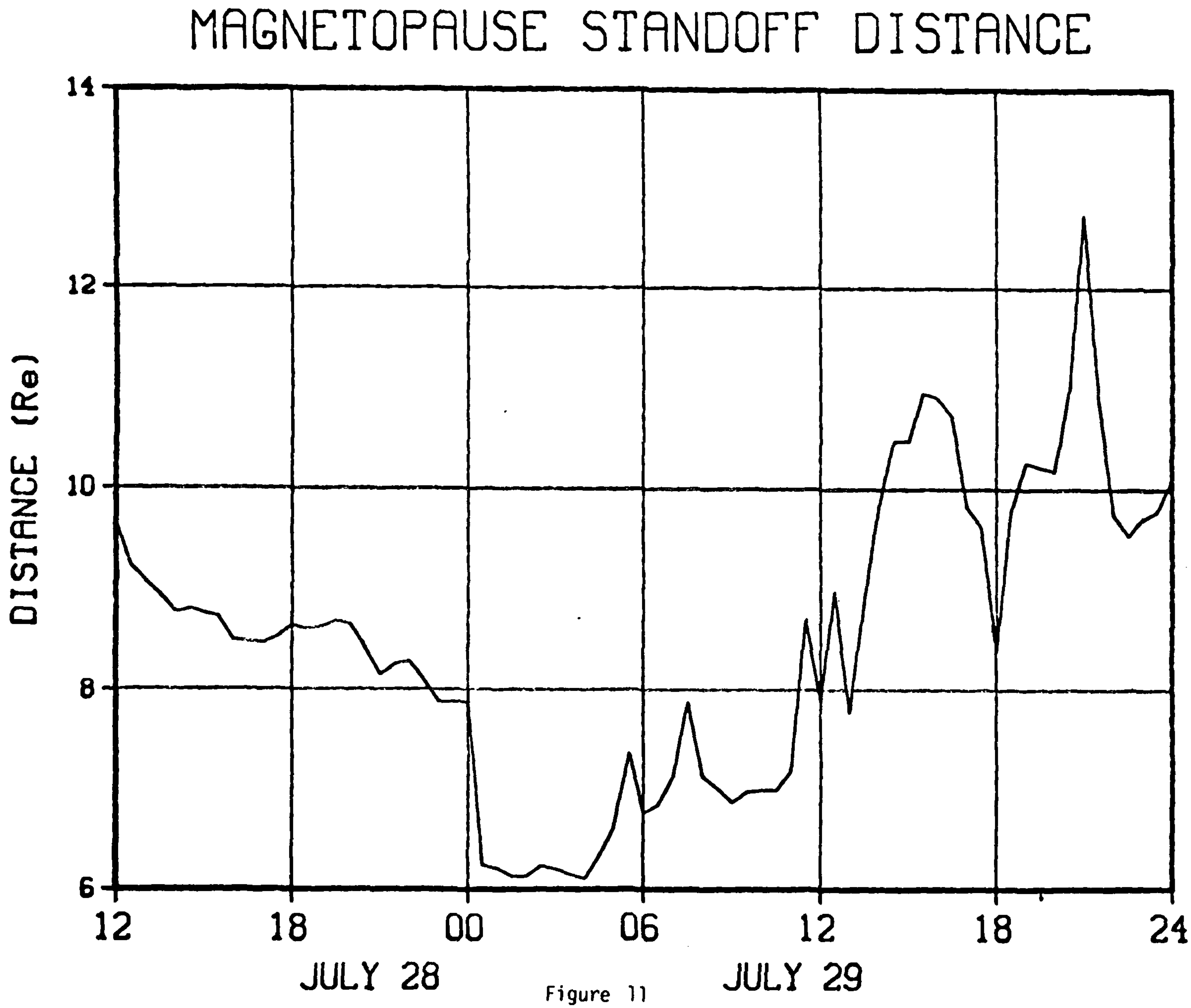

MAGNETOPAUSE STANDOFF DISTANCE
DISTANCE (Re)
14
12
10
8
6
12
18
00
06
12
18
24
JULY 28
JULY 29

Figure 11

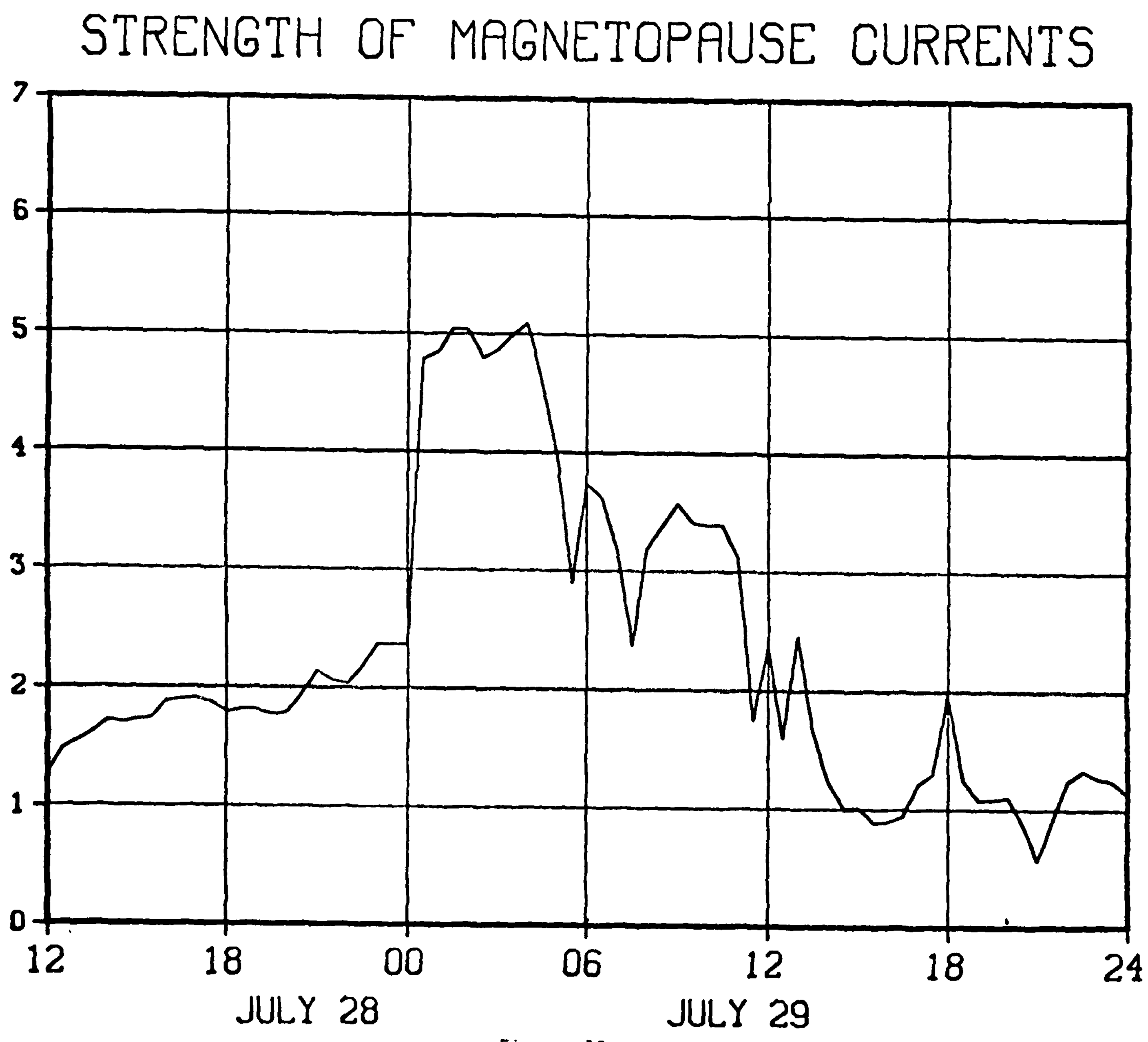

STRENGTH OF MAGNETOPAUSE CURRENTS
7
6
5
4
3
2
1
0
12
18
00
06
12
18
24
JULY 28
JULY 29

Figure 12

become important the agreement between observation and models is not adequate. Large differences between observation and model are present for both events in this region. Thus in order to model the magnetospheric magnetic field in the most dynamic region, the tail, more work is required. This became even more apparent in CDAW-6.

At the CDAW-6 meeting, another pair of events were analyzed. The agreement between the model and the magnetic field observed by the SCATHA satellite is shown in Figure 13 and seen to be almost amazingly good through the first part of the event. This is while the satellite is on the front side of the magnetosphere. Later in the event, however, it is seen that large descrepancies between the model and observations appear. In an attempt to understand the source of the discrepancies, we have subtracted the model field from the field observed by the GOES 2 and 3 satellites at synchronous orbit near midnight (see Figures 14 and 15). This residual field is that portion of the observed magnetic field that cannot currently be accounted for by the dynamic magnetic field models we have used for the CDAWs. It is apparent that this discrepancy cannot be explained in terms of a ring current because that would also impact the results on the day side magnetosphere where agreement between model and observations is excellent. Also the magnetopause currents are too distant from the geosynchronous satellite locations to explain the large changes in magnetic field topology observed there. Thus, the discrepancy is caused either by an earthward motion of the plasma sheet and neutral sheet currents (the earthward edge of this current system would have to be very thin--a small fraction of an earth radius). The other candidate current system is one that is linked to the field aligned currents which close in the equatorial regions of the nightside magnetosphere.
Our work with the CDAW is thus providing us more information on the location of important magnetospheric current systems and associated plasma phenomena in electric fields. We are now exploring the differences between the observed night time disturbed field and our model magnetic field and attempting to relate them to our work on the physics of the magnetopause and particle entry into the magnetosphere.

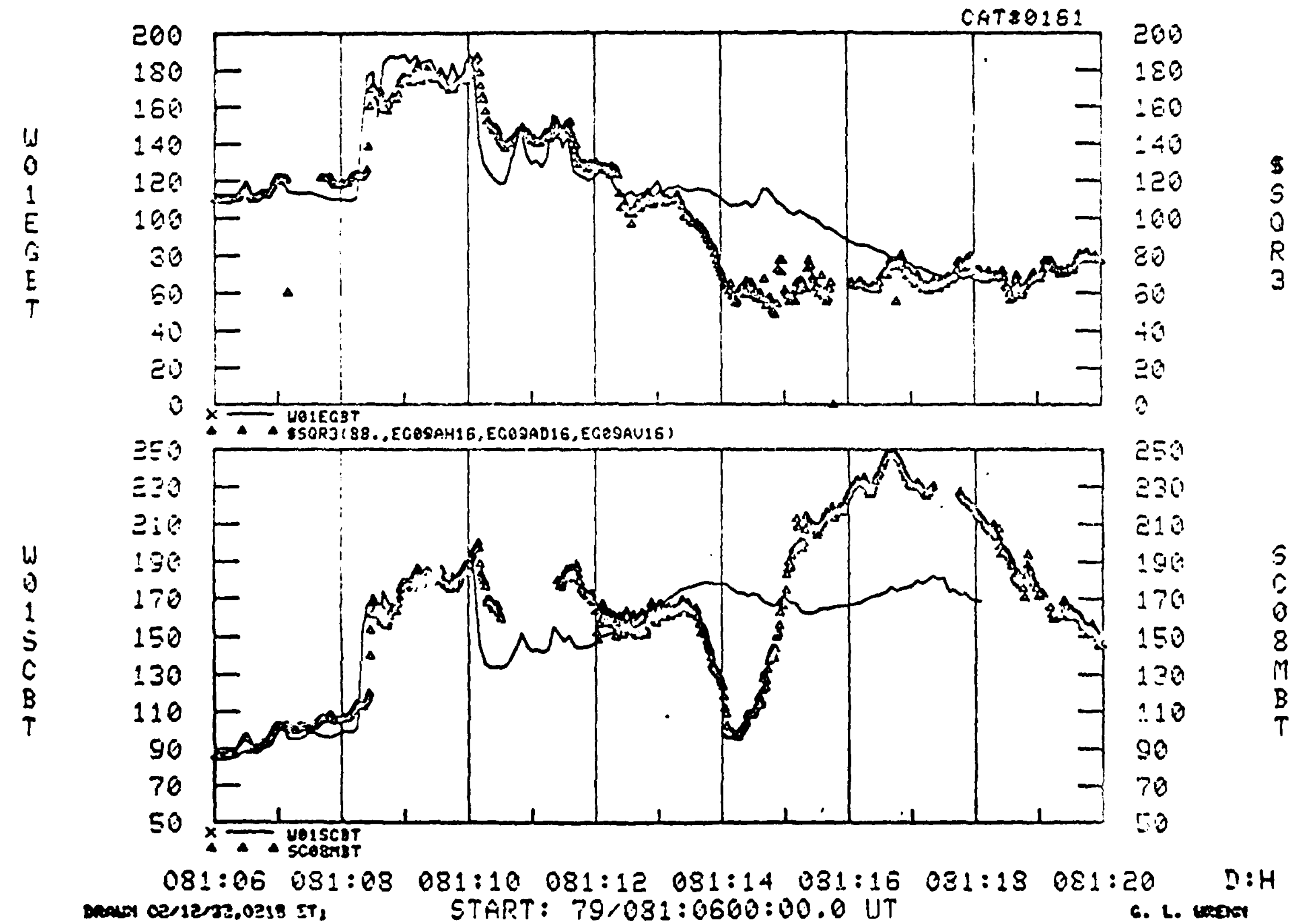

CAT$0161
W01EGET
$SQR3
W01EGBT
$SQR3(88.,EG09AH16,EG09AD16,EG09AV16)
W01SCBT
SC08MBT
081:06 081:08 081:10 081:12 081:14 081:16 081:18 081:20 D:H
DRAWN 02/12/82,0218 ST;
START: 79/081:0600:00.0 UT
G. L. WRENN

Figure 13.

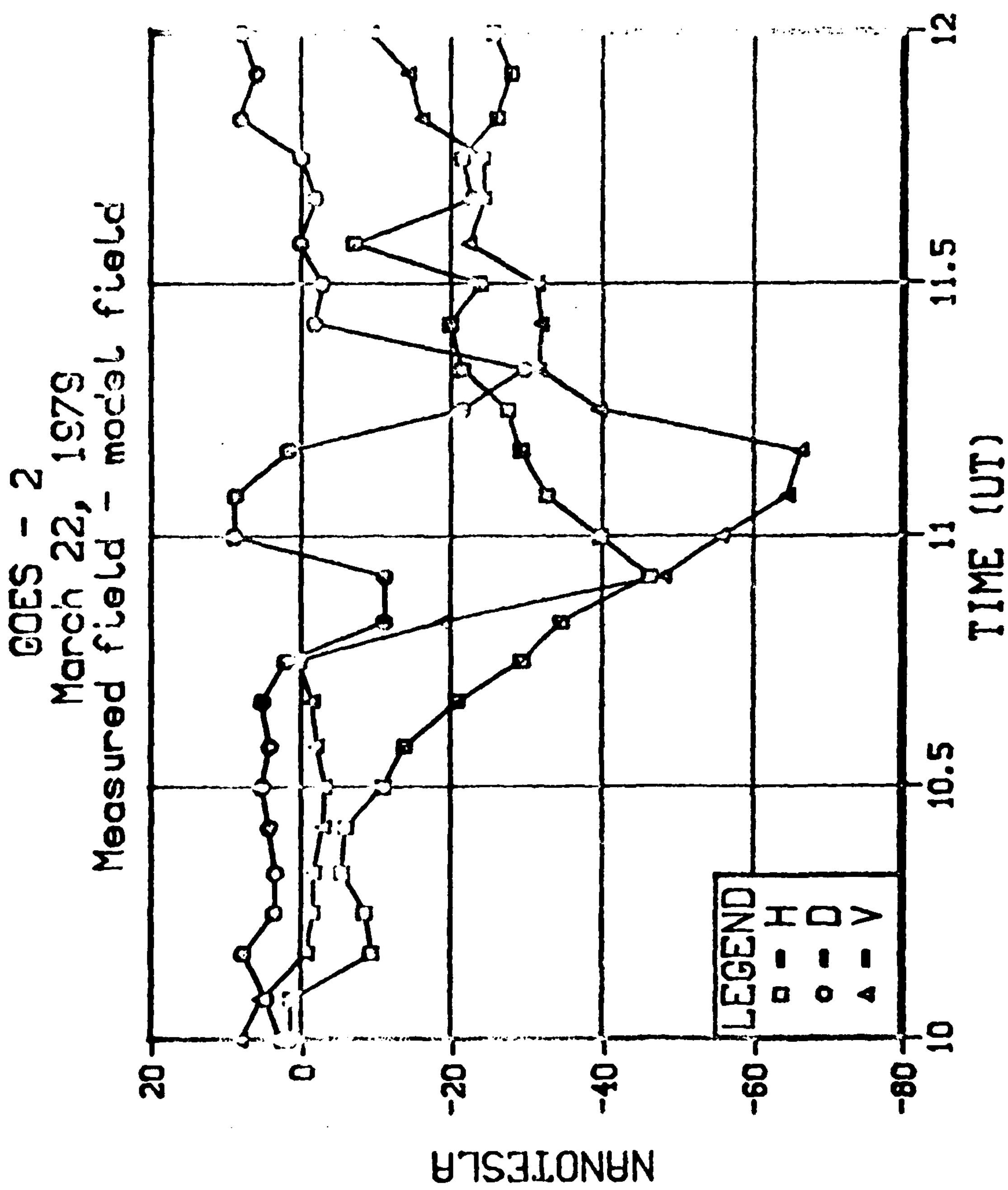

GOES - 2
March 22, 1979
Measured field - model field
NANOTESLA
TIME (UT)
LEGEND
H
D
V
20
0
-20
-40
-60
-80
10
10.5
11
11.5
12

Figure 14.

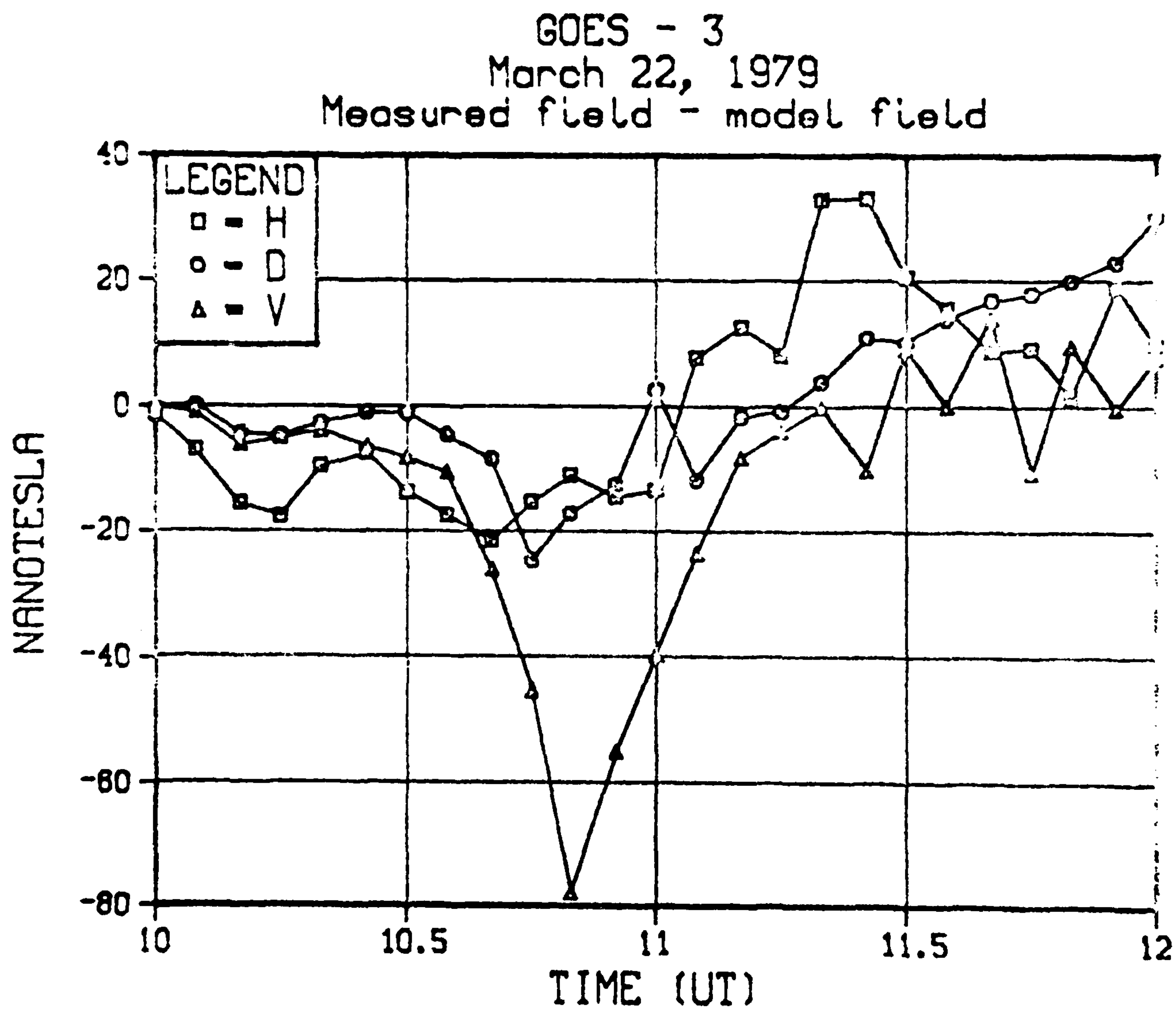

GOES - 3
March 22, 1979
Measured field - model field
LEGEND
□ - H
○ - D
△ - V
NANOTESLA
40
20
0
-20
-40
-60
-80
10
10.5
11
11.5
12
TIME (UT)

Figure 15.

5.0 DISCUSSION AND CONCLUSIONS

During the past year, as described above, we have worked on the microphysics of magnetopause structure, the entry of low energy charged particles into a magnetically closed magnetosphere, and have been active participants in the 6th Coordinated Data Analysis Workshop. The magnetopause microphysics problem is very interesting in its complexity. In fact, it should be of general interest to the plasma physics and MHD communities since it is an example of a problem that requires both local and global solutions simultaneously. This is because the structure of the boundary on one side of the magnetosphere is dependent on charge separation and resultant electric fields caused in part by events on the other side of the magnetosphere. It is apparent from discussions with investigators currently engaged in the application of 3-Dimensional magnetohydrodynamic codes to the magnetosphere problem that the magnetopause microphysics problem cannot be solved with an MHD formalism (because of the problem's local/global nature). We have continued to pursue the problem by having discussions with other members of the theoretical community and hope to understand at least how to formulate the problem in the next months.

We are very excited about our particle entry work. It had been assumed for many years that only very energetic particles (solar and galactic cosmic rays) could enter into a magnetically closed magnetosphere. However, it is quite apparent that even some of the lowest energy particles can penetrate the magnetopause and move through a magnetically closed magnetosphere owing to the finite gradients in the magnetospheric magnetic field at the magnetopause. Most of the entering particles are constrained because of magnetic field topology to flow along magnetic field lines in the antisolar direction. However, near the center of the magnetotail, entering charged particles can actually move across the tail of the magnetosphere. Thus we have stated that we can qualitatively explain the existence of the plasma sheet, plasma mantle and boundary plasmas in the magnetosphere. To date we have not performed detailed calculations of plasma densities in the plasma sheet, etc., because of the lack of data on the particle distribution function for the magnetosheath plasma. Also, our work on particle entry has been restricted to a quiet or static magnetosphere. We hope in the near future to extend this work, using some of the results from the CDAWs, to include dynamic processes occurring in the magnetosphere as solar wind and interplanetary parameters and thus conditions for plasma entry change during "magnetospheric events".

Our work at CDAW-6 has led us to conclude that we understand the day side magnetosphere very well. However, there may be an entire current system that we have not yet isolated that exists in the near tail region in the magnetosphere during disturbed times. Most likely the magnetic residuals (differences between the observed and model values) can be explained in terms of the extension into space of the field aligned currents which flow in the ionosphere at auroral altitudes. We plan in the coming months to develop more realistic input parameters to our existing magnetic field models. These input parameters will, we hope, provide information on the dynamics of the magnetopause, ring and tail current systems that are based on a physical understanding of particle entry into the magnetosphere. The ring current is especially interesting since particles are injected sporadically to supply it. Also, particle loss rates are dependent on the density of the ring current. Hopefully these phenomena can be related back to changes in interplanetary and solar wind parameters. We expect, however, because of energy storage within the magnetosphere, that for both the ring and tail current systems, time integrals over interplanetary and solar wind parameters will have to be developed.

LIST OF PUBLICATIONS AND PRESENTATIONS
MADE DURING THE PAST YEAR

A Dynamic Model of the Magnetospheric Magnetic and Electric Fields for July 29, 1977, to be published in Journal of Geophysical Research, 1982.

Quantitative Magnetospheric Studies Using Magnetic and Electric Field Models. McDonnell Douglas Astronautics Company, Paper No. 8791-I. Presented to the IAGA 4th Scientific Assembly in Edinburgh, Scotland, August 1981.

The Entry of Low Energy Charged Particles into a Magnetically Closed Magnetosphere. McDonnell Douglas Astronautics Company, Paper No. G8792-I. Presented to the IAGA 4th Scientific Assembly in Edinburgh, Scotland, August 1981.

The Contribution of Non-Ionospheric Currents to Variations in the Earth's Surface Magnetic Field. McDonnell Douglas Astronautics Company, Paper No. G8794-I. Presented to the IAGA 4th Scientific Assembly in Edinburgh, Scotland, August 1981.

The Accurate Determination of the Magnetospheric Magnetic Field in the Vicinity of the Earth, McDonnell Douglas Astronautics Company Paper No. 8795-I. Presented to the IAGA 4th Scientific Assembly in Edinburgh, Scotland, August 1981.

The History of the Study of Daily Variations in the Earth's Surface Magnetic Field, McDonnell Douglas Astronautics Company Paper No. G8796-I. Presented to the IAGA 4th Scientific Assembly in Edinburgh, Scotland, August 1981.

The Acceleration of Charged Particles by the Daily Wobble of the Geomagnetic Field, McDonnell Douglas Astronautics Company, Paper No. G8797-I. Presented to the IAGA 4th Scientific Assembly in Edinburgh, Scotland, August 1981.

The Quantitative Representation of the Magnetosphere Electromagnetic Field for Specific Events. McDonnell Douglas Astronautics Company, Paper No. G8798-I. Presented to the IAGA 4th Scientific Assembly in Edinburgh, Scotland, August 1981.

A Dynamic Magnetic Field Model, EOS Trans. AGU 63, 420, 1982, presented to the Spring Meeting of the American Geophysics Union in Philadelphia, PA

APPENDIX

ONE DIMENSIONAL MODELS OF THE MAGNETOPAUSE

INTRODUCTION

The entry of charged particles through the magnetopause is ideally determined when these particles that enter, the ones reflected, and those drifting through from within the magnetosphere self-consistantly determine the magnetopause currents, magnetic and electric fields. Classical magnetopause theory assumes that the only variation of the various field quantities is in the direction perpendicular to the magnetic field direction. This assumption will yield the macroscopic pressure balance equation and specular reflection of all incident particles. The presence of gradients in the magnetic field tangent to the magnetopause has been shown to allow particles to enter a magnetically closed magnetosphere for various energies and incident directions. This calculation was not done self-consistently and there are questions what form the pressure balance will take if there is a net entry through the magnetopause. Also, if electric fields are formed due to the differing entry efficiencies of protons and electrons, how do these fields effect the pressure balance.

We assume that the one dimensional geometry used in classical magnetopause physics (see Grad, 1961; and Hurley, 1963) is adequate since the gradients of field quantities parallel to the magnetopause are much smaller than the ones perpendicular to the magnetopause. The effect of these small gradients will be parameterized by the current perpendicular to the magnetopause. Two "solutions" will be derived here. One is a "macro" solution which is the equivalent of the classical pressure balance equation. The other is a "micro" solution which illustrates the difficulty of doing the detailed kinetic solution even in the simplest cases.

ASSUMPTIONS

We make the one dimensional approximation with the direction perpendicular to the magnetopause x, and the $\mathbf{B}$ field in the z direction. The form of the field vectors is

$$\mathbf{B} = B(x)\hat{\mathbf{z}}$$

$$\mathbf{A} = A(x)\hat{\mathbf{y}}$$

$$\mathbf{E} = E(x)\hat{\mathbf{x}}$$

where we have the relations $B = dA/dx$ and $E = -d\phi/dx$ for the electrostatic potential ϕ. We set up two boundaries. There are particles incident from $x = -\infty$ (i.e. interplanetary space) with prescribed distribution functions F_i defined for directions with $v_x > 0$ where i denotes the different species. The particles incident from $x = 0$ (i.e. the magnetosphere) have the prescribed distribution functions G_i and are defined for directions with $v_x < 0$. Part of the "micro" solution is to determine the total distributions f_i for $-\infty \leq x \leq 0$ that are due to the boundary fluxes F_i and G_i. We assume that the magnetic field is zero at $x = -\infty$ and increases to some unknown value at $x = 0$. The vector potential A will therefore be monotonic with it's value at $x = -\infty$ set to zero. The potential ϕ is also set to zero at $x = -\infty$. We will assume charge neutrality at $x = -\infty$, and if possible, at $x = 0$. The current J_x will be an input parameter. A schematic of the assumptions is shown in figure 1.

The equations to be solved are the Vlasov equation for the particles and two of Maxwell's equations for the fields

$$\mathbf{v} \cdot \partial f_i/\partial \mathbf{r} + (e_i/m_i)\big(\mathbf{E} + \mathbf{v} \times \mathbf{B}\big) \cdot \partial f_i/\partial \mathbf{v} = 0$$

$$\big(\partial/\partial \mathbf{r}\big) \cdot \mathbf{E} = -d^2\phi/dx^2 = (1/\epsilon_0) \sum_i e_i \int f_i \, d\mathbf{v} = \rho/\epsilon_0$$

$$\hat{\mathbf{y}} \cdot \big(\partial/\partial \mathbf{r}\big) \times \mathbf{B} = -d^2 A/dx^2 = \mu_0 \sum_i e_i \int v_y f_i \, d\mathbf{v} = \mu_0 J_y.$$

In the remainder of this section, the subscript i on the charge e, the mass m, and the distribution functions will be supressed for clarity and the summation $\sum$ is assumed to be over all species i. The distribution function f will satisfy Vlasov's equation if the arguements of f are three constants of particle motion. We use

$$\begin{aligned} W &= \tfrac{1}{2}m^2(v_x^2 + v_y^2 + v_z^2) + me\phi \\ P &= mv_y + eA \\ Q &= mv_z \end{aligned}$$

where W is particle mass times the total energy, and P, Q are the generalized momenta in the y and z directions. We will transform the integrals over velocity space into integrals over (W, P, Q) space according to the relation

$$d\mathbf{v} = \frac{dW dP dQ}{\left|\frac{\partial(W,P,Q)}{\partial(v_x,v_y,v_z)}\right|}$$

where the Jacobian is given by

$$\left|\frac{\partial(W,P,Q)}{\partial(v_x,v_y,v_z)}\right| = m^4|v_x|.$$

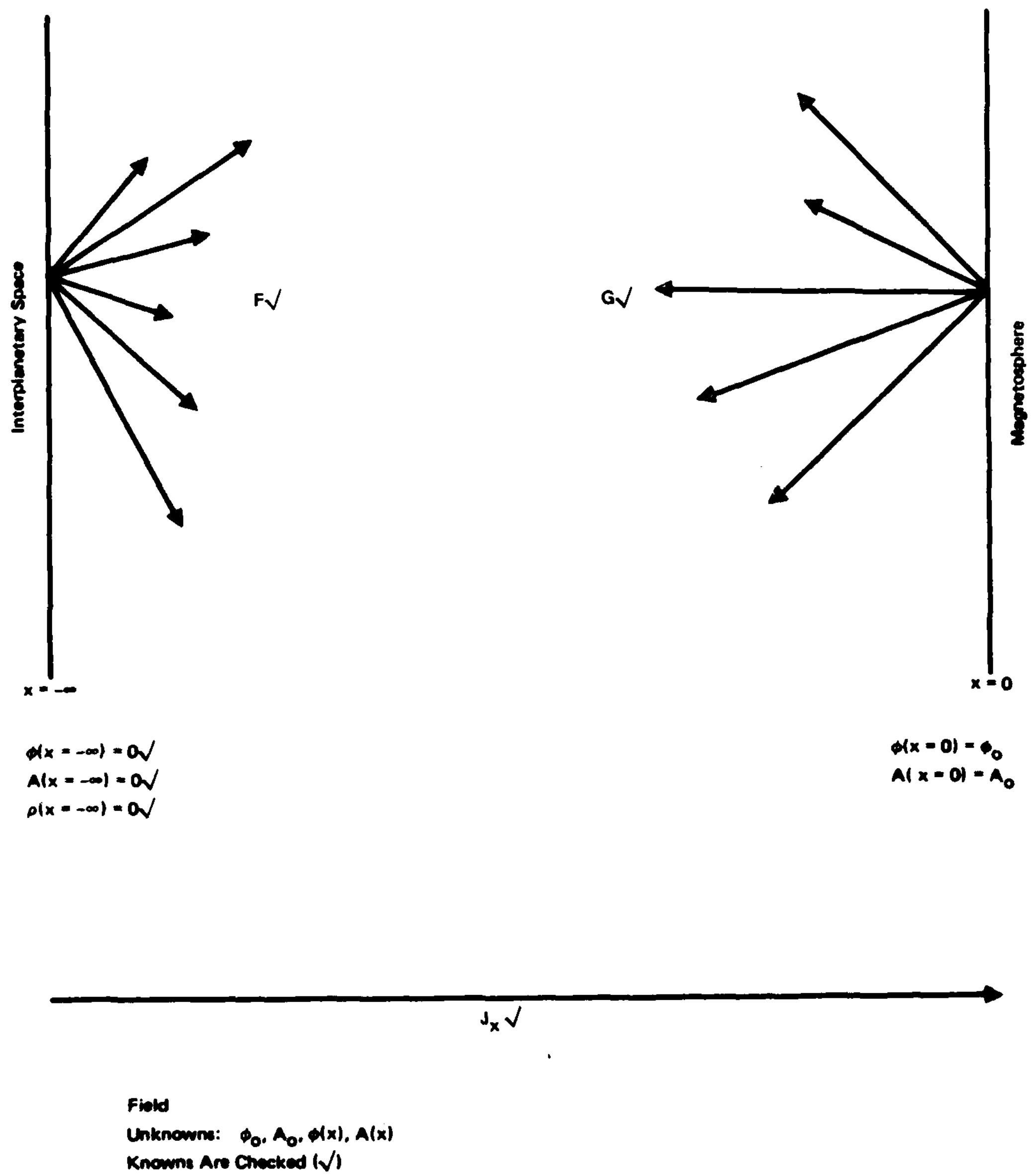


Figure A-1. Problem Schematic

The particle orbits labeled by a given (W, P, Q) must be limited ensure only "allowed" orbits are defined by the distribution function.

PARTICLE ORBITS

Most generally, any set of constants (W, P, Q) at a position x with $A(x)$ and $\phi(x)$ such that

$$2(W - me\phi) - (P - eA)^2 - Q^2 = m^2 v_x^2 \geq 0$$

imply that the particle at x is on a physically valid particle orbit. The eight possible forms of the particle orbits is shown in figure 2. Note that no structure in the y or z directions is implied in this figure. For all particles incident from the boundaries, only orbits 1-4 are valid. We also wish for the simplicity of having all orbits connected, so only cases 1-3 will eventually be allowed.

To avoid cases 4 and 6-8; we must not allow the potential defined by $\psi = 2me\phi + (P - eA)^2 + Q^2$ to have a relative maximum. This is the condition required by Grad (1961) derived from the energy equation, $2W = m^2 v_x^2 + \psi$. Setting $d\psi/dx = 0$ yields $P = eA - E/B$. Requiring that $d^2\psi/dx^2 > 0$ gives us the condition that

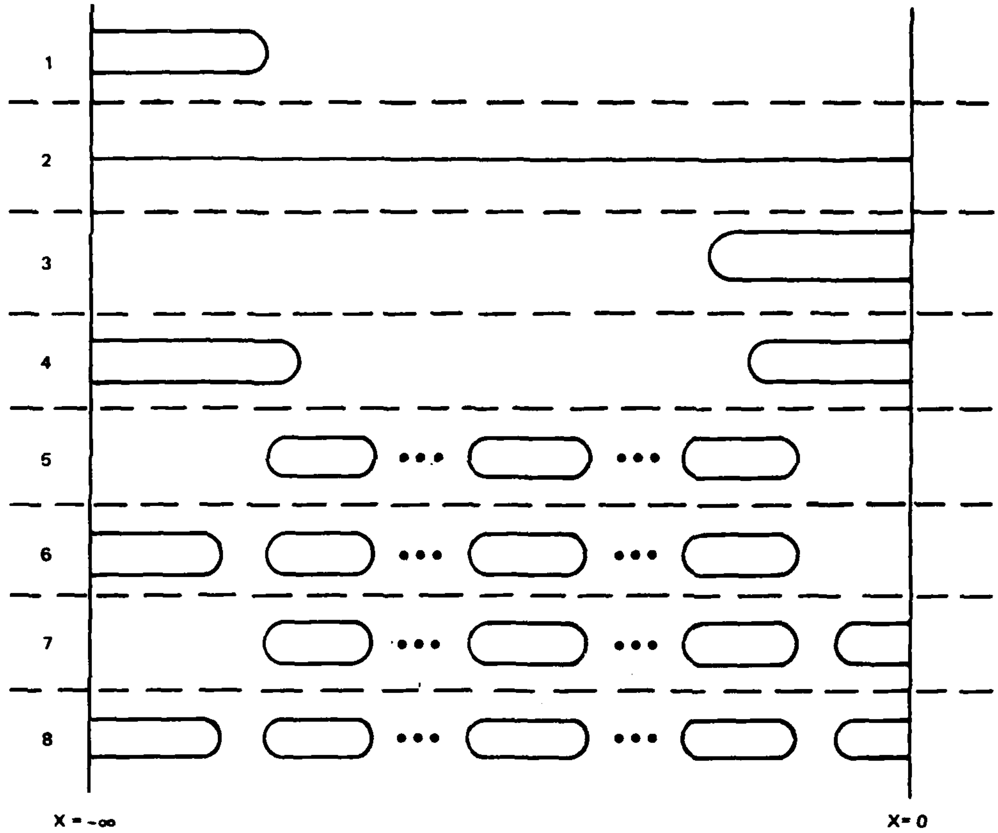
$$(2emE/B)dB/dx + 2em\rho/\epsilon_0 + 2e^2B^2 > 0,$$

which must be checked after a kinetic solution is derived. Note that with no electric field, the result reduces to Grad's restriction that A is monotonic; and that we have also assumed A is monotonic so that B can only go to zero asymptotically. With this restriction for each species, the possible orbits are reduced to the 4 shown in figure 3. To remove case $5a$, we require that orbits be able to reach either the left or right boundaries.

The form of the distribution functions limited to orbits 1-3 will be derived here. Let the function $\Theta(A, \phi) = 2(W - em\phi) - (P - eA)^2 - Q^2$ be defined where the (W, P, Q) dependence is understood. Let A_0 and ϕ_0 be the values of A and ϕ at $x = 0$. Then the distribution function f is given by

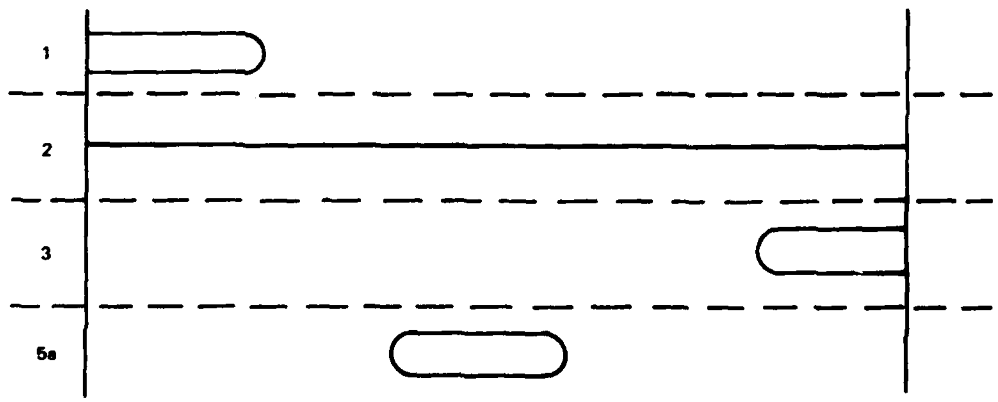
$$\begin{aligned} f(W, P, Q; A, \phi) = {} & F(W, P, Q)H[\Theta(0,0)]\{2H[\Theta(A, \phi)] - H[\Theta(A_0, \phi_0)]\} \\ & + G(W, P, Q; A_0, \phi_0)H[\Theta(A_0, \phi_0)]\{2H[\Theta(A, \phi)] - H[\Theta(0, 0)]\} \end{aligned}$$

where we have suppressed the dependence of f on (A_0, ϕ_0) and H is the Heaviside step function. The dependence of G on (A_0, ϕ_0) results from G given in terms of velocity. Because of these step functions, the integration over (W, P, Q) space can extend over the entire three dimensional space



Physically Possible Orbits

Figure A-2



Orbits With Restriction On Ψ

Figure A-3

$-\infty < W, P, Q < \infty$ which we denote by $\Re^3$. The macroscopic quantities number density n, shielding current j_y, and pressure tensor component p_{xx} due to the distribution function f of a single species are

$$n(A,\phi) = \int_{\Re^3} \frac{f(W,P,Q;A,\phi)}{m^3\sqrt{\Theta(A,\phi)}}\, dW\, dP\, dQ$$

$$j_y(A,\phi) = \int_{\Re^3} \frac{e(P-eA)f(W,P,Q;A,\phi)}{m^4\sqrt{\Theta(A,\phi)}}\, dW\, dP\, dQ$$

$$p_{xx}(A,\phi) = \int_{\Re^3} \frac{\sqrt{\Theta(A,\phi)}}{m^4} f(W,P,Q;A,\phi)\, dW\, dP\, dQ.$$

The macroscopic current j_x of a single species is given by

$$j_x = \frac{e}{m^4}\int_{\Re^3}\{F(W,P,Q) - G(W,P,Q;A_0,\phi_0)\} \cdot H[\Theta(0,0)]H[\Theta(A_0,\phi_0)]\, dW\, dP\, dQ$$

where the dependence on (A_0, ϕ_0) for this as well as the other macroscopic quantities has been supressed.

To explain the use of the step functions, note that $m^2 v_x^2(A,\phi) = \Theta(A,\phi)$. Using the $x = -\infty$ boundary flux as an example; the particles that come from this boundary must have an initial $v_x > 0$ so $\Theta(0,0) > 0$. If they reach x with $(A,\phi) = (A(x),\phi(x))$, then $\Theta(A,\phi) > 0$. If they reach $x = 0$, they will not "reflect" and contribute to flux with $v_x < 0$ so $\Theta(A_0,\phi_0) > 0$. The net contribution to the distribution function f from the left boundary flux is easily seen to be

$$F(W,P,Q)H[\Theta(0,0)]\{2H[\Theta(A,\phi)] - H[\Theta(A_0,\phi_0)]\}.$$

The logic for determining the contribution from the right boundary and j_x is similiar.

Macro Solution – The Pressure Balance

Because of the assumption that A is monotonic, we can use it as a coordinate replacing x. Therefore, the electrostatic potential ϕ can be written as $\phi = \phi(A)$. By taking the total derivative of the pressure p_{xx} with respect to A, we can obtain

$$dp_{xx}(A,\phi(A))/dA = j_y + enE/B.$$

To derive this result, we needed to use several of the relations given above. Also, in taking the derivative inside the integral, we get terms like $\sqrt{\Theta}\,\delta(\Theta)$

where δ is the delta function. These terms integrate out to zero. Summing over all species we find

$$\begin{aligned} \rho &= \sum en \\ J_y &= \sum j_y \\ J_x &= \sum j_x \\ P_{xx} &= \sum p_{xx} \\ dP_{xx}/dA &= J_y + \rho E/B. \end{aligned}$$

From Maxwell's equation, we find that

$$-d^2A/dx^2 = \mu_0(dP_{xx}/dA - \rho E/B)$$

which we integrate from $A = 0$ (i.e. $x = -\infty$) to A (i.e. x). The first term integrates to

$$\begin{aligned} \int_{A=0}^{A} d^2A/dx^2\, dA &= \int_{x=-\infty}^{x} d^2A/dx^2(dA/dx)\, dx \\ &= \int_{x=-\infty}^{x} \tfrac{1}{2} d(dA/dx)^2/dx\, dx = (dA/dx)^2/2 = B^2/2. \end{aligned}$$

The second term integrates to

$$\int_{A=0}^{A} dP_{xx}/dA\, dA = P_{xx} - P_{xx}(0,0)$$

where $P_{xx}(0,0)$ is the value at $x = -\infty$. The last term becomes

$$\begin{aligned} \int_{A=0}^{A} \rho E/B\, dA &= \int_{x=-\infty}^{x} (\rho E/B)(dA/dx)\, dx \\ &= \int_{x=-\infty}^{x} \rho E\, dx = \int_{x=-\infty}^{x} \epsilon_0 E(dE/dx)\, dx = \epsilon_0 E^2/2 \end{aligned}$$

Adding these integrals up and using the relation $\mu_0\epsilon_0 = 1/c^2$ where c is the speed of light, we get the pressure balance condition

$$P_{xx}(x = -\infty) = P_{xx} + B^2/2\mu_0 - E^2/2\mu_0 c^2.$$

The last term gives the electric field's effect on the classical pressure balance. Unless the electric field is very large (on the order of 1 volt/meter for the earth's magnetopause), the electric field has only a small effect on the pressure balance.

MICRO SOLUTION – THE BOUNDARY VALUE PROBLEM

The solution to the kinetic problem involves two of Maxwell's equations which are coupled through the current J_y and charge density ρ. At the boundary $x = 0$, the quantities (A_0, ϕ_0) are unknown, but the can be found from the known conditions. The current J_x and the charge neutrality at $x = -\infty$ are assumed known. Since these quantities are functions of (A_0, ϕ_0), we can in principle solve for these boundary values. The equations to be solved are

$$-d^2\phi/dx^2 = \rho(A, \phi)/\epsilon_0$$
$$-d^2A/dx^2 = \mu_0 J_y(A, \phi)$$

where the boundary conditions at $x = -\infty$ are

$$A = 0$$
$$\phi = 0$$

and the boundary conditions at $x = 0$ (i.e. (A_0, ϕ_0)) are found from

$$\rho(0,0) = 0$$
$$J_x = J_{\text{known}}$$

which are two equations for the two unknowns (A_0, ϕ_0).

MICRO SOLUTION – A SIMPLE EXAMPLE

To illustrate the above micro solution, we solve a simple example that allows no particle entry, but does form an electric field. We assume that a beam of mono-energetic particles is incident normally on the magnetopause. The distribution functions for incident ions and electrons are

$$F_i = \frac{m_i^3\sqrt{2}\,n_\infty}{2\sqrt{W_i}\,P_iQ_i}\delta(W/W_i - 1)\delta(Q/Q_i)\delta(P/P_i)$$

and

$$F_e = \frac{m_e^3\sqrt{2}\,n_\infty}{2\sqrt{W_e}\,P_eQ_e}\delta(W/W_e - 1)\delta(Q/Q_e)\delta(P/P_e)$$

where $W_e, W_i > 0$. Letting e be the positive electron charge, the integral J_x is

$$J_x = \frac{en_\infty}{\sqrt{2}}\{(\sqrt{W_i}/m_i)H[2(W_i - em_i\phi_0) - e^2A_0^2]$$
$$-(\sqrt{W_e}/m_e)H[2(W_e + em_e\phi_0) - e^2A_0^2]\}.$$

We assume J_x is zero so for general W_i and W_e, we have

$$
\begin{aligned}
2(W_i - em_i\phi_0) - e^2A_0^2 &\le 0 \\
2(W_e + em_e\phi_0) - e^2A_0^2 &\le 0.
\end{aligned} \tag{*}
$$

The current J_y is given by

$$
J_y = -e^2An_\infty \left\{ \frac{\sqrt{2W_i}\,H[2(W_i - em_i\phi) - e^2A^2]}{m_i\sqrt{2(W_i - em_i\phi) - e^2A^2}} + \frac{\sqrt{2W_e}\,H[2(W_e + em_e\phi) - e^2A^2]}{m_e\sqrt{2(W_e + em_e\phi) - e^2A^2}} \right\}
$$

when we apply the above condition at $x = 0$. In fact, we can let the inequalities in (*) be equalities so that the current J_y will exist up to $x = 0$. The charge density is given by

$$
\rho = en_\infty \left\{ \frac{\sqrt{2W_i}\,H[2(W_i - em_i\phi) - e^2A^2]}{\sqrt{2(W_i - em_i\phi) - e^2A^2}} - \frac{\sqrt{2W_e}\,H[2(W_e + em_e\phi) - e^2A^2]}{\sqrt{2(W_e + em_e\phi) - e^2A^2}} \right\}
$$

where the step functions will be equal to 1 in the range $-\infty < x < 0$ by the equality condition in (*).

The charge density derived above can be set to zero so that a quasi-neutral relation between ϕ and A is obtained. The result is that

$$
\phi = \phi_0(A/A_0)^2
$$

where

$$
\begin{aligned}
\phi_0 &= \frac{1}{e}\frac{W_i - W_e}{m_i + m_e} \\
A_0 &= \frac{2}{e^2}\frac{m_iW_e + m_eW_i}{m_i + m_e}
\end{aligned}
$$

are the solutions to the equalities in (*). The only differential equation left to solve is Maxwell's equation

$$
d^2A/dx^2 = -\mu_0 J_y = \frac{\mu_0 e^2 n_\infty}{\sqrt{1 - A^2/A_0^2}}\left(\frac{1}{m_e} + \frac{1}{m_i}\right).
$$

The change of variable from x to $\alpha = A/A_0$ will transform the equation to

$$dB^2/d\alpha = \frac{B_0^2\alpha}{\sqrt{1-\alpha^2}}$$

where $B_0^2 = 2A_0^2e^2n_\infty\mu_0(1/m_e + 1/m_i)$. The solution of this differential equation is

$$B^2 = B_0^2(1-\sqrt{1-\alpha^2})$$

where the value of B^2 at $x = 0$ (i.e. $\alpha = 1$) is in fact B_0^2 defined above. Since the x derivative of A is B, the solution for B^2 gives us another differential equation to solve. We can manipulate it into the form

$$dx/d\alpha = \frac{A_0}{B_0\sqrt{1-\sqrt{1-\alpha^2}}}$$

which has the normalized solution

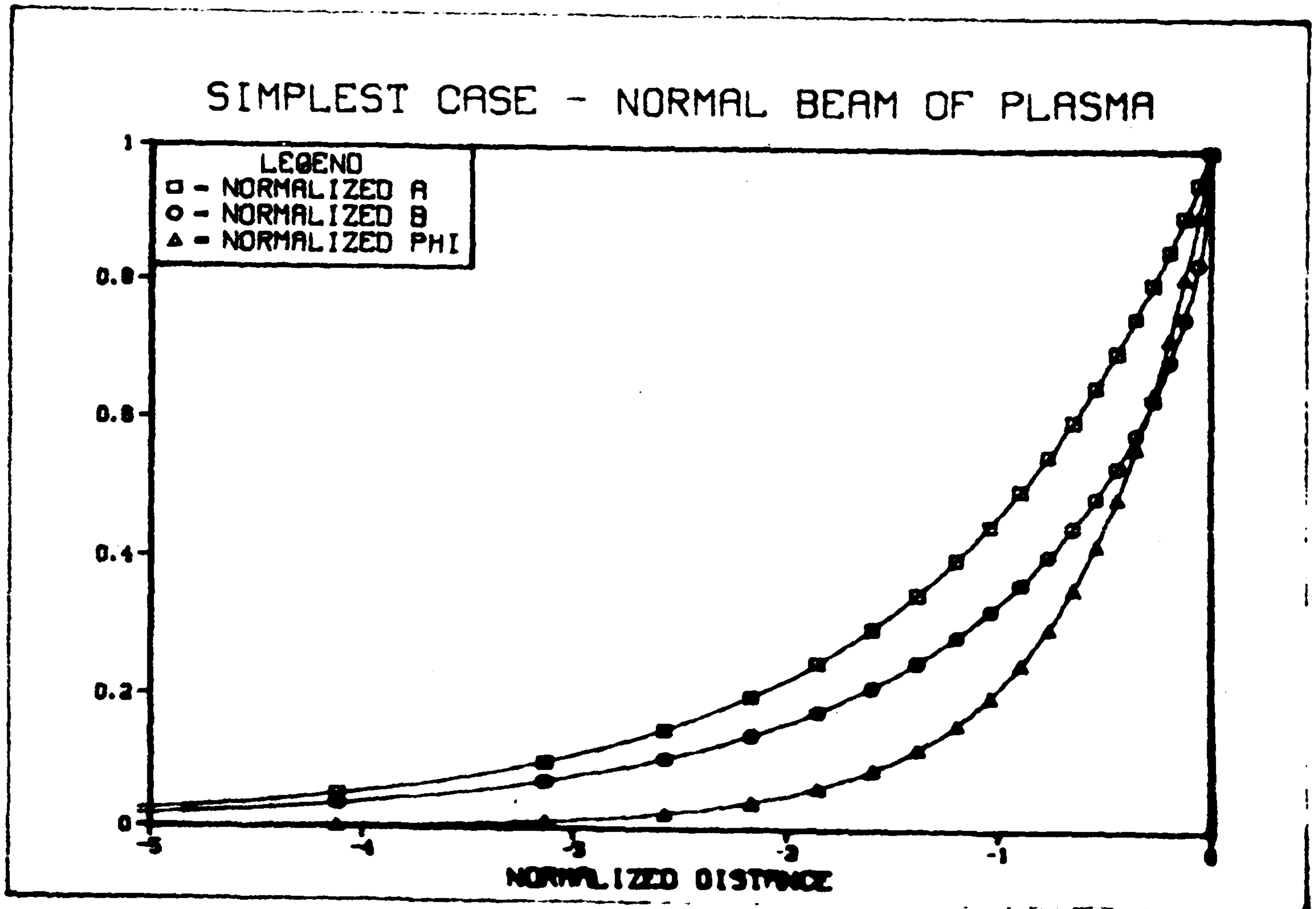
$$\frac{B_0}{A_0}x = 2\left(\sqrt{1+\sqrt{1-\alpha^2}}-1\right)+\sqrt{2}\ln\left(\frac{\sqrt{2}-\sqrt{1-\sqrt{1-\alpha^2}}}{(\sqrt{2}-1)\sqrt{1-\sqrt{1-\alpha^2}}}\right).$$

Figure 4 shows the dependence of normalized A, B, and ϕ on normalized distance for this simple problem.

DISCUSSION

The kinetic example above was the simplest magnetopause problem of interest that could be solved in closed form. In this quasi-neutral solution, we could throw out one differential equation and luckily the other could be solved analytically. There is no current through the magnetopause but there is an electric field whose sign is determined by the particle with the larger incident momentum, $\sqrt{2W}$. Because these particles are monoenergetic, there are only three discrete currents J_x possible. A more realistic problem with incident beams having a continuous energy distribution would allow a continuum of J_x currents to be specified; however, this problem will be very difficult to solve if it is possible to solve at all.

The kinetic, micro/solution approach is seen to be difficult, but it can give us all the details of the solution if we want them. If all we want is the potential ϕ_0 inside the magnetopause, we will not need to solve the differential equations. The incident distribution functions must still be known and the coupled integrals for $\rho(x=-\infty)$ and J_x solved for (A_0, ϕ_0). The macro/solution will not yield the electric field since it will be a small



SIMPLEST CASE - NORMAL BEAM OF PLASMA
LEGEND
□ - NORMALIZED A
○ - NORMALIZED B
△ - NORMALIZED PHI
1
0.8
0.6
0.4
0.2
0
-5
-4
-3
-2
-1
0
NORMALIZED DISTANCE

Figure A-4

residual of the classical pressure balance. Because the pressure balance is essentially a MHD equation, the MHD simulations can not be expected to yield an electric field formed by particle interaction at the magnetopause even if the resolution near the magnetopause was adequate.

A possible way to solve the magnetopause problem with out having to solve Maxwell's equations would be to use **B** field gradients to determine current J_x and solve for (A_0, ϕ_0) as described above; substitute these values in the integrals for P_{xx} inside and outside the magnetopause; and use the pressure balance to determine B inside the magnetopause. The distribution functions for particles incident from inside the magnetosphere are still needed. These have entered from another position on the magnetopause, so a global solution of the state of the entire magnetosphere is necessary.